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PROPULSION TECHNOLOGY NEEDS FOR ADVANCED SPACE TRANSPORTATION SYSTEMS

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Abstract

Plans have been formulated for chemical propulsion technology programs to meet the needs of advanced space transportation systems during the two decades from 1980 to the year 2000. The many possible vehicle applications have been reviewed and cataloged to isolate the common threads of primary propulsion technology that will satisfy near term requirements in the first decade and at the same time establish the technology groundwork for various potential far term applications in the second decade. Two thrust classes of primary propulsion engines are apparent: (1) 5,000 to 30,000 pounds thrust for upper stages and space maneuvering; and (2) large booster engines of over 250,000 pounds thrust. Six major classes of propulsion systems and the important subdivisions of each class have been identified. The relative importance of each class is discussed in terms of the number of potential applications, the likelihood of that applicaton materializing, and the criticality of the technology needed. Specific technology programs are described and scheduled to fulfill the anticipated primary propulsion technology requirements of the period.

Introduction

During the decade of the 1980's most of the NASA and DOD space transportation requirements will be provided by the Space Shuttle, which is now under development. The Space Shuttle vehicle system, shown in figure 1, includes the Orbiter vehicle, an external hydrogen-oxygen tank (ET), and dual solid rocket booster (SRB) motors. An additional part of this space transportation system (STS) is an upper stage that will be transported to low earth orbit in the Shuttle cargo bay and used to propel payloads to higher orbits or to escape velocity. Initially, this requirement will be met by a modified existing stage, such as Transtage, Centaur, Agena, or Delta, called the Interim Upper Stage (IUS). Later, a full capability, reusable Space Tug will be developed, which will be operational after 1984.

The principal incentive for development of the Space Shuttle system is reduction of launch vehicle cost through re-use of major portions of the launch vehicle. The Orbiter vehicle, the SRB cases, and eventually the Space Tug will be re-used from 50 to 100 missions. Reusability of the Shuttle system will reduce the launch vehicle portion of payload costs from the present level of $800 to $1000 per pound of payload in low earth orbit to approximately $150 to $200 per pound. Also, when the full capability Tug is developed the Shuttle system will provide new capabilities such as spacecraft retrieval from synchronous orbit, on-orbit servicing of spacecraft, and frequent ferry missions to a manned orbiting space station.

Since the present baseline STS is well into the development phase, it is timely to examine modifications to the propulsion system that have potential for improving the present system in key areas, such as operating cost, payload capability, operational flexibility, and environmental impact. In the latter half of the decade from 1980 to 1990, a number of Shuttle "growth" improvements merit consideration, including, for example: changing of Orbiter subsystems, such as the Orbit Maneuvering System (OMS); replacement or improvement of the SRB's; or uprating of the Space Shuttle Main Engine (SSME). Also, alternatives to the present baseline cryogenic Tug or improvements to the Tug or IUS may be considered. Beyond 1990, new Space Transporation Systems are being studied, such as: single-stage-to-orbit (SSTO) shuttles using mixed mode propulsion systems[1], fully reusable two-stage-to-orbit (TSTO) vehicles, and a variety of other vehicle types.

Study Guidelines

The primary propulsion technology needed for the advanced STS of the 1980-2000 time period was evaluated with the objective of identifying propulsion technology needs and evolving a comprehensive technology plan to meet those needs. Various vehicle applications were studied that appeared likely to occur in the two decades, which were referred to as: (1) the near term (1980-1990) period; and (2) the far term (1990-2000) period. The program was, therefore, designed to provide a flow or evolution of technology from the presently definable near term applications to more advanced far term applications. Study of the propulsion systems needed for these applications quickly revealed a natural division into two engine thrust classes, as shown in figure 2: (1) Space engines of approximately 5,000 to 30,000 pounds thrust having general application to upper stages, space maneuvering systems, or lunar surface vehicles; and (2) Booster engines of generally greater than 250,000 pounds thrust that provide the high thrust levels needed for vehicle lift-off and propulsion to low earth orbit.

Also shown in figure 2 are examples of specific applications for each engine thrust class in both the near term (1980 to 1990) and far term (1990 to 2000) time periods. The near term applications represent improvements to the present STS or existing expendable launch vehicles and the far term applications represent vehicles that may replace or supplement the present STS or meet other contemplated requirements.

In laying out this technology plan, no attempt was made to compile an exhaustive list of potential vehicle types or applications but rather to prepare a listing of typical applications having emphasis on various propulson system attributes such as thrust level, performance, cost, storability, density, etc. Also, no attempt was made to emphasize or champion any particular vehicle application or propulsion system type. The objective was, instead, to provide a propulsion technology plan that will provide efficient use of R&T funds through prudent selection of technology programs having both foreseeable near term and potential far term applications, most significant payoff, and greatest likelihood of use.

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Schedule

The Space Shuttle is now being developed and will be in operational use beginning in 1980, as shown in figure 3. The IUS will also be operational by 1980 and, according to present plans, will be replaced by the Space Tug in 1984. Development of the Tug is scheduled to start in 1978. The present NASA stable of expendable launch vehicles, including Atlas-Centaur, Titan-Centaur, Thor-Delta, and Scout, will be used into the early to mid 1980's, after which they will gradually be phased out and replaced by the Shuttle. The exception to this is the Scout vehicle which because of its low cost will continue to be used for small payloads. The various Shuttle "growth" options previously mentioned could be brought into operational use as early as 1986 through block changes to the vehicle system, which would require that development of these options be initiated by 1980-1981. To meet these time schedules for near term applications, the primary propulsion technology work must be vigorously pursued during the 1976 to 1981 time period. This will provide needed technology in time for these early applications and lay the groundwork for a continuing and somewhat overlapping technology program for the far term applications during 1979-1985. This schedule will provide the propulsion technology for advanced STS vehicles in time to start development by about 1985 in order that they may be operational by about 1990. These schedules for improved or new vehicles are not necessarily advocated, but are presented only to enumerate the possibilities and to show the scheduling of advanced technology needed if these options are to be exercised.

Applications

5,000 to 30,000 Pounds Thrust – Near Term

IUS – The Interim Upper Stage will be a modified existing upper stage, such as Delta, Agena, Centaur, Transtage, or Burner II, as shown in figure 4. These stages have been studied extensively as either expendable[2] or reusable stages and one (or possibly two) will be selected by late 1975. The IUS is conceived as a low cost approach to providing the needed upper stage for the Space Shuttle by 1980, rather than developing a new stage at the same time as the Shuttle is being developed. Because of the emphasis on low cost and limited operational time period, it is not likely that the IUS, as now envisioned, will have need for much advanced technology. However, because of the unknowns regarding the projected mission model, the vagaries of NASA budgets and funding priorities, and the questions regarding the value of payload retrieval and stage re-use, it is possible that the IUS use period may be extended and that performance improvements and advanced technology infusion may therefore be considered. For example, if a modified Centaur stage, as shown in figure 5, were selected as the IUS, one approach to improving it would be to replace the RL10 engines with a new higher performance engine. Then, at a later time, when the cryogenic Space Tug is developed it could use the same new engine. This approach would spread the total Tug development cost (including the new engine) over a greater number of fiscal years and would be an acceptable approach if payload retrieval (which the IUS will not provide) were not actually needed by 1984 (as is now planned in the mission model), and if the payload capability of the uprated IUS were adequate.

Space Tug – The present baseline Tug vehicle, shown in figure 6, is a high performance, cryogenic reusable stage that uses a modified RL10 engine[3]. Other Tug vehicle concepts are also being studied including higher performance cryogenic systems, plug nozzle engines, multi-staged solid rocket motor systems, and high bulk density liquid propellant systems, such as N_2O_4 – amine fuel, LOX-amine fuel[4] or LOX-hydrocarbon fuel. All of these approaches have certain advantages and the final selection will depend upon the relative emphasis given to various design considerations, such as payload capability, cost, stage length, reusability, payload retrieval, and operational considerations.

If the presently baselined hydrogen-oxygen propellants are retained for the Space Tug, higher performance may be achieved by the use of more advanced engine systems, such as the staged combustion cycle Advanced Space Engine (ASE)[5] or the aerospike engine[6]. Extensive efforts have been in progress for several years to develop the technology for these engines in order to make them viable options for the Tug. Both of these advanced engines can provide higher payload capability and reduced engine length compared to the RL10 category IIB engine. The higher development cost for one of these advanced engines would eventually be defrayed by a reduction in the number of Shuttle flights needed to perform the mission model and savings in payload development costs resulting from increased payload margin.

Shuttle OME – The Space Shuttle has two Orbit Maneuvering Engines (OME), housed in two separate removable pods on the aft end of the fuselage, which are used for attaining orbit, maneuvering in space, and de-orbit. The OME is a 6000-pound thrust, pressure-fed engine that burns N_2O_4-MMH propellants. A number of approaches may be considered for improving this system, such as substituting a higher performance pump-fed engine and propellant feed system or use of different propellants that are lower in cost or higher in performance. Possible candidates are N_2O_4-hydrazine, LOX-hydrocarbons, or LOX-liquid hydrogen. The system using LOX with an intermediate density hydrocarbon fuel provides high bulk density, improved specific impulse, and reduced propellant cost. However, it would require development of long duration, low pressure LOX storage systems that would fit within the present pods. The oxygen-hydrogen system, because of its low bulk density and hydrogen storage problems, would require more extensive changes to the Shuttle Orbiter vehicle, but would provide a high performance system burning clean, non-corrosive propellants that are ideal for a reusable system.

Expendable Upper Stages – The present NASA family of expendable vehicles includes the Atlas-Centaur, Titan-Centaur, Thor-Delta, and Scout. Since these vehicles will be in use until the mid-1980's, it is reasonable to investigate various methods for improving or uprating them provided the changes are relatively low in cost and provide significant advantages. Also, in studies being made of mission requirements in the 1990's[7], these expendable launch vehicles in modified form are being included in the study as part of the overall vehicle mix that may provide lowest total cost, which, of course, is dependent upon the mission model of the 1990's. The upper stages used on these vehicles are the same ones being considered for the IUS and, therefore, the same advanced propulsion technologies apply for the most part to both the IUS and uprated versions of these expendable stages.

For example, if a high performance staged combustion cycle ASE of 15,000 pounds thrust were developed and used on the (Centaur) IUS and later the Space Tug, it could also be used to uprate the Centaur stage for Atlas-Centaur and Titan-Centaur missions. On Atlas-Centaur missions, such as Intelsat and FLTSATCOM, the Centaur stage is employed to place the spacecraft into a highly elliptic transfer orbit. The payload exchange factor for such missions is plus 28 pounds of payload per second increase in specific impulse[8]. Use of two ASE's to replace the present RL10A-3-3 engines on Centaur would provide an increase in specific impulse of 25 seconds and fit within the same approximate physical envelope. The resulting increase in payload of 700 pounds would increase Intelsat IVA payload by 22% and FLTSATCOM payload by 18%. This payload increase could provide: additional communications capability; increased life and reliability through added redundancy and greater attitude control propellant weight; or reduced cost through use of lower technology (heavier) equipment and heavier, standardized components.

5,000 to 30,000 Pounds Thrust – Far Term

Advanced Space Tug – Assuming that the Tug becomes operational in the mid-80's, as presently planned, it is reasonable to consider methods for uprating or improving it by 1990 or soon thereafter as the mission model of the 1990's becomes clearer. Such improvements are difficult to define at present because several different concepts are still being considered for the Tug. Such improvements could take the form of high performance hydrogen-oxygen systems, high density propellant systems, use of fluorinated oxidizers, or use of mixed mode propulsion. If the present baseline cryogenic tug design is developed, a logical method of uprating would be by replacement of the modified RL10 engine with a higher performance staged combustion cycle engine (ASE) or aerospike (plug nozzle) engine as previously mentioned for the IUS.

Another promising concept for an advanced tug is the use of mixed mode propulsion(9). In this approach, shown in figure 7, first LOX-RJ-5 and then LOX-LH_2 propellants would be burned in series in a single, staged-combustion, dual fuel engine. The payload capability for this design would be comparable to the baseline cryogenic Tug but the payload volume available would be increased by up to 34%. In a more recent study of mixed mode propulsion for tug(16), even more advantageous stage designs were achieved using LOX/MMH/H_2 propellants with a dual fuel engine.

Payload volume will become increasingly important for Shuttle missions of the late 1980's and beyond and will increase the emphasis upon compact, short length Tug designs. Compilation of data from the 1973 Shuttle Cargo Manifest Data(10) table shows that the average planned cargo length is 51.2 feet, or over 85% of the available length (based on use of 35 foot length Space Tug), whereas the average cargo load factor is about 69% or 44,600 pounds of payload. Thus, a superficial study of the Shuttle cargo situation indicates more margin exists for payload weight growth than for payload length growth. Consequently, short length (but high performance) Tug designs should be of considerable interest in the future. Also, any future uprating of Tug payload capability will be constrained by the cargo bay volume limitation, again placing importance upon shorter length Tug designs.

Orbit Transfer Vehicle – In long range planning studies of potential missions in the 1985-1995 time period(11), an Orbit Transfer Vehicle (OTV) is prominently mentioned as a key element of the overall space transportation system. The OTV is larger than the tug but would be used for similar missions, for example, to move payloads from low earth orbit to geosynchronous orbit, to transport spacecraft to the vicinity of the moon, or to propel spacecraft to escape velocity. Vehicles of various sizes, from approximately 100,000 to 500,000 pounds total weight, are being studied and both LO_2/LH_2 and high density propellants, such as LO_2/MMH, are being considered. This application calls for an advanced engine in the range from 20,000 to 40,000 pounds thrust having compact size (high chamber pressure), high specific impulse, tank head ullaging and start, and long life with no limit on restarts. Either conventional bell nozzle or plug nozzle engines could be employed singly or in clustered arrangements, one example of which is illustrated in figure 8.

Lunar Surface Vehicle – In the studies of future mission requirements(11), lunar exploitation missions are also being evaluated. These missions would require advanced vehicles for landing and taking off from the lunar surface. Some of the concepts under study, as shown in figure 9, are sized to be Shuttle payload bay compatible and could be modified forms of the OTV mentioned above. Various sizes, staging configurations, and propellants are applicable, including LO_2/LH_2 and high bulk density propellants, such as LO_2/MMH or LO_2/RJ-5. This application also requires an advanced high performance engine having the characteristics mentioned above for the OTV with the additional feature of throttling for the landing stage.

Orbit Maneuvering Systems – Future advanced shuttle-type vehicles, which may be single-stage-to-orbit designs, will require on-board propulsion, like the Shuttle OME, for supplying the final ΔV to reach orbital velocity, maneuvering and rendezvous with payloads in space, and de-orbit propulsion. Such systems generally do not have the same degree of emphasis upon high performance as the Tug or OTV and, consequently, a pressure-fed or moderate pressure pump-fed engine may be adequate. However, the design requirements of the specific application will dictate the choice of propulsion system. Technology generated for the Tug and OTV will be applicable for advanced OMS although the thrust level needed for orbit maneuvering is generally lower, e.g., 5,000-10,000 pounds thrust per engine.

Over 250K Thrust – Near Term

SSME Improvement – The Space Shuttle Main Engine (SSME), shown in figure 10, is a 470,000 pound vacuum thrust, staged combustion cycle hydrogen-oxygen engine that operates at a chamber pressure of 2970 psia. Three SSME's are mounted in the Orbiter vehicle and burn continuously from launch to near orbital velocity, delivering high specific impulse that varies from 363 seconds at take-off to 455 seconds in vacuum.

Because the engine must operate over widely varying back pressures, the nozzle expansion area ratio of 77:1 was selected as a compromise. A lower area ratio would give better performance at sea level and a larger area ratio would provide higher performance at space vacuum conditions. Therefore, the overall engine performance could be substantially improved by a variable area ratio or two-position nozzle that could be changed to more nearly match the nozzle area ratio to the optimum value as pressure ratio changes during the flight. Engine performance could also be improved by the use of an altitude compensating (plug) nozzle or by increasing the engine chamber pressure, which allows for a higher expansion area ratio nozzle. Such performance improvements will provide higher Shuttle payload capability, which has the effect of reducing the average cost per pound of payload in orbit, assuming launch costs remain constant.

If the chamber pressure of the SSME were increased to 4000 psia, for example, the nozzle area ratio could be increased to 97 within the present physical envelope, which would provide an increase in vacuum specific impulse (I_{sp}) from 455 to 460 seconds. Since the Shuttle payload is increased 1320 pounds per 1 second increase in I_{sp} of the SSME, this change would provide a potential payload increase of about 6600 pounds or 10% of the present payload capability. This added capability could also be utilized to provide compensation for Shuttle weight growth, longer stay times in orbit, or alleviation of Tug propulsion requirements.

Shuttle SRB Improvement – As shown in Figure 1, two 142-inch diameter solid rocket booster (SRB) motors are attached to the external tank of the Shuttle. The SRB's burn in parallel with the main propulsion system (3 SSME's), providing thrust augmentation of about 5,000,000 pounds during the initial phase of launch, up to a velocity of 4470 feet per second. After their burn is completed, the SRB's are released by pyrotechnic separation devices and separate from the ET. The SRB's then descend into the ocean by parachute and are recovered, refurbished, and re-used.

The solid rocket boosters were selected for the Shuttle because of their simplicity, reliability, and low development cost compared to a liquid booster. However, they have certain disadvantages, including high recurring cost and pollution of the atmosphere. The SRB's presently constitute about one-third of the Shuttle recurring cost per flight, which is primarily due to the high propellant cost, predicted to be about $1.00-$1.25 per pound. The present SRB propellant formulation is a mixture of ammonium perchlorate, aluminum, and PBAN binder. A reduction of propellant cost of about 10-15% could be achieved by substituting HTPB binder, a change that is now contemplated. Another problem related to the solid propellant is contamination of the upper atmosphere with HCl and other products in the exhaust which may cause ozone depletion or other air pollution problems. To solve this problem, consideration is being given to substituting ammonium nitrate for ammonium perchlorate in the propellant mixture. However, this change would cause a reduction in I_{sp} of about 3 to 4 seconds and a concomitant reduction in Shuttle payload of about 1400 to 1800 pounds. Also, the use of ammonium nitrate is less desirable from the standpoint of safety and ease of handling.

Shuttle SRB Replacement – Because of the high recurring cost and atmospheric contamination problems of the SRB's, a number of options have been considered for replacing them with liquid propellant boosters(7). The options studied generally have the goals of: (1) making maximum use of Shuttle hardware presently being developed, i.e., using the Orbiter and external tank with minimum modifications; (2) maintaining payload capability at the present level of 65,000 pounds or increasing it; and (3) providing a low development cost system which can provide a significant reduction in Shuttle recurring cost. Some examples of the types of vehicles being considered are shown in figure 11.

Figure 11(a) shows a Shuttle growth concept in which the SRB's have been replaced with dual strap-on liquid propellant booster stages. The boosters burn LOX/RJ-5 propellants and require development of an advanced high pressure LOX/RJ-5 engine of 1.8 million pounds thrust. The liquid boosters stage off like the present SRB's and are parachuted into the ocean, recovered, re-furbished and re-used. An alternative recovery method is to fly the boosters back as unmanned RPV's (remotely piloted vehicles) and land them horizontally on land. This approach eliminates the problems associated with ocean recovery and refurbishment of salt water exposed engines but introduces new problems and considerably higher development cost of deployable wings, air breathing propulsion, and RPV flyback equipment.

The concept shown in figure 11(b) replaces the SRB's with a heat sink flyback booster that has five F-1 engines burning LOX/RP-1 propellants. The booster uses S-IC propellant tanks and has wings, tail, and air breathing propulsion for the flyback portion of the mission. The existing Orbiter vehicle and shortened external tank (ET) are also utilized. The booster and Orbiter operate in series burn mode rather than parallel burn like the present Shuttle.

Figure 11(c) illustrates a third concept in which the present Orbiter and ET are retained and the SRB's are replaced with a flyback booster. The booster has internal LOX and RJ-5 tanks and has three high performance LOX/RJ-5 engines of 1.77 million pounds thrust each. This booster development represents the first step of a two-step process to arrive at a fully reusable two-stage Shuttle system with manned flyback booster. The second step is to develop a new Orbiter stage having the same external mold line as the booster but with internal hydrogen and oxygen tanks (thus eliminating the ET) and four high pressure H_2-O_2 engines. The concept shown in figure 11(c) has a payload capability of 65,000 pounds with the booster stage propellants off-loaded. If fully loaded, the payload capability is increased to 140,000 lbs. but the Orbiter cargo bay volume is probably insufficient to accommodate this payload weight.

Expendable Launch Vehicle Improvement – As previously mentioned, the present stable of expendable launch vehicles is slated to be phased out in the early-to-mid 1980's. However, if the Shuttle program schedule slips or if its recurring cost per flight increases significantly, some of these vehicles may continue to be flown through the 1980's for certain types of missions. In this event a variety of improvements may be considered to uprate vehicle performance, reduce cost, or improve operational characteristics. These improvements may include, for example, use of advanced high performance engines, substitution of high density hydrocarbon fuel (RJ-5) for kerosene (RP-1) fuel, various improvements to solid propellant motors, or use of air augmentation to provide high specific impulse at vehicle lift off and during the early portion of the flight.

Over 250K Thrust – Far Term

Single-Stage-to-Orbit (SSTO) – In recent years the single-stage-to-orbit shuttle concept has been studied extensively(12,13) in the search for future booster vehicles capable of reducing Earth-to-orbit transportation costs below $100/pound. The SSTO shuttle appears capable of meeting this recurring cost goal through the efficiencies associated with use of a fully reusable, single-stage vehicle as opposed to two or two-and-a-half stage concepts, like the present Shuttle. Of the many SSTO designs studied, the mixed mode concept of the type shown in figure 12, appears most promising. This particular vehicle design employs eight high pressure staged combustion O_2/RJ-5 engines of 680K sea level thrust each and two dual fuel engines of 588K vacuum thrust each. The dual fuel engine(1) is designed to burn O_2/RJ-5 propellants during the boost phase of flight and switch to O_2/H_2 during the sustain mode, at which time all the O_2/RJ-5 engines are shut off. The dual fuel engine is not essential to make the mixed mode SSTO a viable concept, but improves it by reducing total engine weight and vehicle boattail area required. Separate O_2/H_2 and O_2/RJ-5 engines have been employed in either series burn or parallel burn arrangements in other SSTO designs. Because of the high ΔV required of the single stage shuttle, a very efficient propulsion system employing advanced high performance engines is necessary. For the O_2/RJ-5 boost phase, high pressure staged combustion cycle engines, such as shown in figure 13, are needed. Alternative arrangements have also been studied(14) utilizing linear throat/plug nozzle or linear plug cluster nozzle concepts, shown in figure 14. These designs have the advantage of better utilization of boattail area, improved structural efficiencies associated with thrust take-out from the engines to the vehicle, and better sea level I_{sp} resulting from the use of altitude compensating nozzles.

Two-Stage-To-Orbit (TSTO) – A variety of fully reusable two-stage-to-orbit shuttle vehicle concepts were evaluated in the Space Shuttle Phase B studies. This vehicle concept has the advantage of lower recurring cost than the present baseline Space Shuttle (figure 1). For example, the TSTO vehicle shown in figure 15 is predicted to have a recurring launch cost of $16 per pound of payload in low earth orbit. This vehicle is the second phase of the vehicle development described above, the first phase of which is shown in figure 11(c). The complete TSTO consists of two manned stages having the same external mold line that are mounted belly-to-belly for launch. All tanks are internal and no hardware is expended on each flight. The orbiter stage has four high pressure H_2/O_2 engines of 380K sea level thrust each.

Many other TSTO concepts have been proposed to meet the mission requirements of the 1990's including both vertical takeoff, horizontal landing vehicles (VTOHL) and horizontal takeoff, horizontal landing (HTOHL) vehicles. The VTOHL concepts are generally all rocket propelled; the HTOHL concepts utilize composite engines in the first stage that combine air breathing propulsion and rockets within a single engine. Composite engine concepts will be described in greater detail in a following section. The HTOHL concepts, an example of which is shown in figure 16, provide low recurring cost and generally tend to have lower GLOW and higher dry weight than comparable all-rocket powered VTOHL designs.

Assisted Takeoff Concepts – Special cases of the SSTO concept are being studied for the far term period that utilize takeoff assist propulsion for the purpose of reducing the size, weight, and cost of the orbiter stage. Some examples of these assisted HTOHL concepts include sled launched, in-flight refueled, or air launched designs. From the standpoint of propulsion technology these concepts introduce no additional requirements for the far term period not covered by the SSTO or TSTO except the possible need for moderate sized solid rocket motors. Other special requirements such as rapid in-flight propellant transfer from a tanker aircraft to the orbiter stage are also introduced.

Heavy Lift Vehicles – To meet many of the projected mission needs of the 1990's(11) and to provide greatly reduced numbers of Shuttle flights for other missions, heavy lift vehicles are needed. These vehicles are postulated to have payload capability to low earth orbit in the range from 150,000 to 400,000 pounds. For payloads of this magnitude, it is essential that vehicle launch costs be minimized and typically launch costs of $25-$50/pound of payload are predicted. This level of cost can be achieved only through reusability of the majority of booster hardware.

Figure 17 illustrates three typical examples of the many possible vehicle types that have been postulated. Figure 17(a) shows a vehicle derived from Shuttle hardware that is capable of transporting 170,000 pounds to low earth orbit. It utilizes the Shuttle external tank and SRB's with three SSME's mounted on the aft end of a payload capsule. The SRB's would be recovered in the same manner as for the present Shuttle and the ET would be expended. The SSME's and the Instrument Unit (IU) would be recovered from orbit by the Space Shuttle for re-use. The vehicle shown in figure 17(b) is designed to place 400,000 pounds in orbit and also makes use of Shuttle-derived components. It has a core H_2/O_2 stage with six SSME's, and four SRB strap-ons. Again, the SRB's would be recovered in the same manner as for the present Shuttle, the IU would be picked up in orbit by the Shuttle and returned for re-use, and the SSME's would be de-orbited in a capsule and recovered by paraglider or parachute. The H_2/O_2 tankage would be expended. The third vehicle, shown in figure 17(c), is also designed for 400,000 pound payload capability but utilizes more advanced technology than the other two. It is a 2-stage series-burn VTOVL (vertical takeoff, vertical landing) design having a central H_2/O_2 stage with a large split combustor aerospike engine and six LOX/RJ-5 strap-on boosters with advanced, high pressure engines. The six LOX/RJ-5 boosters stage-off at 3000-3500 ft/sec velocity and are recovered like the Shuttle SRB's. This recovery mode for the liquid boosters assumes a weight penalty for strengthening the tanks and engines and sealing them for water impact. The core stage is designed for ballistic re-entry and vertical landing using the H_2/O_2 aerospike engine for thrust during the landing maneuver.

Expendable Launch Vehicle Improvement – For the reasons mentioned previously under the Over 250K Thrust – Near Term category, it is possible that some expendable launch vehicles may continue to be used in the 1990's. If this occurs, the advanced technology developed during the next ten years may be applied to uprate and improve these vehicles.

Propulsion System Classification

A set of propulsion system classifications was devised based on the vehicle applications described above for the near term and far term time periods and the two classes of engine thrust level. These classifications, listed in Figure 18, are divided according to the fuel density (high density vs hydrogen) and state of technology development (high pressure vs low pressure) for liquid bipropellant engines, with solids and composites (rocket/air breathers) in separate classifications. Each class is divided into two or three subdivisions and the vehicle applications for each subdivision are shown for the near term and far term periods and for the two engine thrust levels. This chart is intended only to show possible applications and does not advocate any particular one. The characteristics of each classification are explained below.

High Performance, High Density Systems – These systems employ advanced high pressure, pump-fed engines designed to deliver high specific impulse and have compact size and high thrust-to-weight ratio. The types of propellants are characterized by high density fuels, such as the hydrocarbon or amine families, with oxidizers, such as liquid oxygen, liquid fluorine or FLOX mixtures, nitrogen tetroxide, or various acids. The types of engines are divided according to nozzle type and include: (1) bell (Delaval) nozzle; and (2) plug nozzle, which includes aerospike, plug cluster arrangements, and unconventional annular throat or linear nozzle concepts. The under 30K bell nozzle engines have application in the near term for Space Tug and Shuttle OME improvements. The large thrust engines have application to the SRB replacement concepts and to expendable launch vehicle improvement. In the far term the bell nozzle engines have application virtually across the board for both large and small thrust requirements partly because these vehicles are not well defined at present and the relative value of high propellant density is unclear. The under 30K thrust plug nozzle engines are applicable in near term to the Space Tug where the Shuttle payload bay volume constraint places a premium on short engine length. The large thrust plug nozzle engines are applicable to some of the SRB replacement concepts. In the far term, plug nozzle engines are applicable to a number of large and small thrust applications, particularly where the advantages of altitude compensation, short length, and integration with the vehicle design are important. Fluorinated oxidizers (Fluorine, FLOX, OF_2, etc.) are listed separately because they introduce a special set of technology problems that tend to limit their use to special applications. These problems include safety, atmospheric contamination, toxicity, high cost, and handling and storage. For under 30K thrust engines in the near term, fluorinated oxidizers are applicable to uprating the IUS or expendable launch vehicles. In the far term for under 30K thrust engines, the most likely application for fluorinated oxidizers is an advanced tug vehicle. No applications are shown for fluorinated oxidizers in large (booster) engines for either near or far term because of the atmospheric contamination and cost problems.

High Performance Hydrogen Fueled Systems – These systems employ liquid hydrogen fueled engines that operate at high chamber pressure and high mixture ratio. The design emphasis is on high stage performance, high delivered specific impulse, compact engine size, and high thrust/weight ratio. The oxidizers include liquid oxygen, liquid fluorine, FLOX, and oxygen difluoride. Subdivisions include bell nozzle and plug nozzle engine types, as described above, and fluorinated oxidizers as a separate category.

The under 30K thrust H_2 fueled bell nozzle engines have many applications in both the near and far term periods. The large thrust bell nozzle engines in the near term have one application – the uprated SSME for Shuttle, but in the far term have several potential applications. The under 30K plug nozzle engines in the near term have application to the IUS and Tug where the advantage of short engine length is important. For large thrust H_2 fueled plug nozzle engines the only application in the near future is for some of the SRB replacement options. In the far term the plug nozzle engines have many potential applications in both thrust level classes. Fluorinated oxidizers have application only for the under 30K thrust class in either near or far term for the same reasons stated above.

High Performance Dual Fueled Systems – These systems include the features and propellants of Classes I and II, but make use of dual fuel engines[1] The dual fuel engine is designed to operate on high density propellants during the boost phase of flight and on hydrogen fuel during the sustain phase. The original concept proposed by Rudi Beichel[1], shown in figure 19, was designed to burn first LOX/RJ-5 and than LOX/LH_2 and is oxygen cooled. It is a high chamber pressure, staged combustion, bell nozzle engine. Other potential dual fuel engine configurations include fuel or auxiliary fluid cooling and plug nozzle designs employing a split combustor. The dual fuel engine is implicitly part of a mixed mode propulsion system (see figure 7). Such systems have potential application in the near term only for under 30K engines of bell or plug nozzle design for th Space Tug where the mixed mode concept can provide short stage length. In the far term dual fuel engines with either bell or plug nozzle are applicable to the Space Tug or OTV for small thrust and to the SSTO or assisted SSTO for large thrust.

Low Development Cost, High Density Fueled Systems – These systems are characterized generally by low cost and low to moderate operating pressures. The propellants are the same as Class I. There are two distinct subdivisions in this class: (1) moderate pressure, pump-fed systems; and (2) pressure-fed systems. The former are characterized by the present state-of-the-art in operational, pump-fed engines, such as the Agena (YLR-BA-9), Atlas Booster and Sustainer, F-1, etc., which have chamber pressures generally less than 1000 psia and utilize gas generator turbopump drive cycles. Selection of such engines for future applications will be made primarily on the basis of cost rather than performance. The pressure-fed systems typically have engine chamber pressures below 200 psia and tank pressures below 500 psia.

Moderate pressure, pump-fed engines have potential applications generally across the board for both thrust classes and both near and far term. Pressure-fed engines have applications where low cost, reliability, ruggedness, and simplicity are predominant factors in the selection of a propulsion system compared to high specific impulse and light weight. In the near term, pressure-fed engines of under 30K thrust are applicable to the Shuttle OME and for over 250K thrust to certain SRB replacement options that propose use of strap-on liquid pressure-fed boosters. In the far term, pressure-fed engine of less than 30K size could be employed on the OTV, orbit maneuvering systems on future shuttle vehicles, or lunar landing vehicles. Large thrust pressure-fed engines are applicable to TSTO vehicles in the far term or heavy lift vehicles.

Composite (Rocket/Air Breathing) Systems – Composite engines[15] combine the features of an all-rocket propulsion system (burning only propellant stored on board the vehicle) and an air breathing engine, which obtains its oxidizer from the atmosphere and its fuel from on-board storage. The basic types of composite engines are shown in figure 20. This class is divided into two subdivisions on the basis of engine complexity. The first subdivision, shown in figure 20(a), is the air augmented or ducted rocket, which consists of a rocket enclosed within a duct. The rocket acts as an ejector pump to ingest air which increases the net thrust and specific impulse of the engine. The other types of composite engines, shown in figures 20(b), (c), and (d), are all more complex, heavier, and involve either secondary propellant combustion, or rotating machinery, or both. These types, the ejector ramjet, air turborocket, and LACE, and many combinations and variations thereof, are included in the second subdivision. They all need considerable technology work prior to development.

Composite engines are only applicable to the booster vehicle applications requiring large thrust engines, since these would be operated in the atmosphere. In the near term only air augmentation is a viable candidate composite engine, since the other subdivision of this class of engines will require more time to develop. Air augmentation could be used to improve the Shuttle SRB performance or for uprating of expendable launch vehicles. The more complex composite engines, such as ramjets, turborockets, LACE, etc., have application in the far term to TSTO or possibly assisted takeoff SSTO vehicles.

Solid Rockets – Solid rocket systems are clearly a separate and distinct class of propulsion systems. The technology for solids is well advanced and they have wide application for both large and small systems in the near term. Solids are employed for the Burner II stage that is being considered for a kick stage for IUS or Tug and for the Scout vehicle. In the large thrust class, applications include the Shuttle SRB improvement and improvement of the solids used on expendable launch vehicles, such as Titan III-Centaur and Thrust-Augmented Thor (TAT)-Delta. In the far term for large thrust motors, applications include the (solid motor) assisted takeoff SSTO and some concepts of the heavy lift vehicle.

Propulsion Technology Needs

In the preceding discussion, a set of six major propulsion system classifications was presented and a preliminary study made of the future vehicle applications that appear possible for each class. The list of potential vehicle applications, although not exhaustive, is nevertheless broad and undoubtedly includes space program options that, because of budget limitations, will never be exercised. In planning propulsion technology programs to be pursued in the next few years, it is therefore, essential to consi which vehicle options appear most likely to be developed. equal importance is consideration of which propulsion technologies have broad application to a number of vehicle options and are, therefore, more apt to be utilized.

A set of priority ratings was devised to assist in prioritizing the need for propulsion system technology for the many vehicle applications. The priority ratings are as follows:

Priority Ratings

1. Very Important	-	Clear payoff; move out with technology work.
2. Important	-	High payoff expected; move out with studies to clarify
3. Desirable	-	Payoff possible; merits further consideration
4. N/A	-	Not applicable

Figure 21 shows the priority ratings assigned for the six major propulsion system classes and their subdivisions for the near term and far term periods for under 30,000 pounds thrust and over 250,000 pounds thrust engines. These ratings reflect the need for propulsion system technology in each category, the payoff expected in terms of improved vehicle performance, the time criticality of the technology as a pacing item needing to be done quickly to provide a viable vehicle or propulsion system choice, and the relative uncertainty that the perceived payoff can be or is likely to be realized. The priority ratings also can be thought of as inversely proportional to investment risk, i.e., a low priority rating (i.e., a 2 or 3) infers a higher risk that the technology dollar invested may not pay off in the development of a useful system that will be applied.

Based on these assigned priority ratings, a logic diagram, shown in figure 22, was devised, which shows the approach for planning of technology work. This plan focuses on near term technology needs on the premise that these areas require an immediate start to meet near term needs and that the technology generated will also have general application to far term requirements. For priority 1 areas, a detailed propulsion technology program must be started in FY 76 to meet the overall schedule of figure 3. Also, vehicle/propulsion system studies should be initiated to further clarify vehicle requirements, compare alternative approaches for various missions, and provide guidance as to selection of most promising approaches. For priority 2 areas, similar vehicle/propulsion system studies should be initiated and, simultaneously, some technology work started that has general applicability or that requires long lead time to solve critical technology problems. Within two years, these areas should be reassessed, decisions made on most promising applications, and propulsion system options narrowed. At that time, a more firm detailed propulsion technology program can be planned. For priority 3 areas, studies are needed to determine feasibility and to provide preliminary information upon which to base decisions on further interest. Following this, if interest remains, vehicle/propulsion system studies should be performed and later detailed technology work initiated.

Following are descriptions of recommended propulsion technology programs for three areas: (A) High Density Fueled Systems; (B) High Performance Hydrogen Fueled Systems; and (C) Solid Rocket Motors. Each program includes discussion of priority 1 areas and long lead time priority 2 work. Following the description of Solid Rocket Motor work is a listing, item (D), of four priority 2 studies that are recommended.

(A) High Density Fueled Systems – The detailed propulsion technology program for high density fueled systems is shown in figure 23. This program is aimed principally at the priority 1 large thrust class systems in Class I, High Performance High Density Fueled Systems, but also will provide considerable basic technology applicable to lower thrust systems and to Class IV, Low Development Cost, High Density Fueled Systems and Class III, High Performance Dual Fueled Systems. The program is divided into 5 categories according to the technical disciplines or engine components involved; each category is discussed below.

(1) Propellant Characteristics – The candidate fuels are: members of the amine family, such as hydrazine (N_2H_4), N_2H_4-UDMH blends, and monomethyl hydrazine (MMH), with nitrogen tetroxide (N_2O_4) or liquid oxygen (LOX) as oxidizer; and the hydrocarbon family, such as RP-1, RJ-5, and a number of others with LOX as oxidizer. The selection of a particular propellant combination from this group will depend upon specific system design characteristics and the relative importance of specific impulse, density, cost, and operational characteristics. The hydrocarbon family, a sample of which is shown in Table 1, includes a large number of candidate fuels that offer wide ranges of density, I_{sp}, and cost. A number of these candidate fuels appear promising for future missions in that, compared to RP-1, they offer higher I_{sp} and higher density. Studies are needed to characterize some of these fuels, obtain property data, examine manufacturing processes, and evaluate relative advantages compared to RP-1/LOX as a standard. If one of the more exotic fuels, like RJ-5 or H-COT dimer, is selected, a production scale-up will be needed to produce quantities required for rocket engine testing. Also, basic heat transfer data from high pressure heated tube tests will be needed as design information for rocket thrust chambers. This will include data on thermal decomposition of the fuel at elevated temperatures.

(2) Thrust Chamber/Combustor Technology – Data is needed on cooling of rocket thrust chambers with high pressure supercritical oxygen. Little data now exists on oxygen heat transfer coefficients at pressures above 2000 psia and subcritical temperatures. High pressure combustion fundamentals, performance, and stability data must also be obtained and supporting analysis performed to obtain correlation between prediction and experimental results. After selection of the fuel and cooling method to be employed (fuel, oxidizer, or auxiliary fluid) for engines of specified size and operating conditions, complete cooled thrust chambers will be demonstration tested to obtain performance and cooling data. Thrust chamber life tests will then be made to evaluate thermal fatigue cyclic life for several hundred cycles of operation. The thrust chamber/combustor program will be focused primarily on bell nozzle engines but may also be expanded to include aerospike/linear engines as interest dictates.

(3) Engine Systems – Studies are planned of high performance, high pressure engine systems for high density propellants to evaluate cooling limitations and turbopump drive cycles and provide parametric data on engine weight and performance vs thrust level. These studies will include both bell nozzle and aerospike/linear nozzle type engines. Engine preliminary designs for specific applications will be complete after selection of cooling method, fuel/oxidizer combination, a[illegible] engine operating conditions. This will provide guidance fo[illegible] following work to "home in" on specific operating conditions for a selected application. Altitude performance data will be obtained with the cooled thrust chamber hardware following demonstration of cooling and performance in (2), above.

(4) Turbomachinery – The principal technologies needed in this area are: development of high temperature turbine materials to allow higher efficiency and extraction of higher specific power from the turbine working fluid; and development of long life bearings and seals capable of a minimum of 10 hours operating life and several hundred starts. Evaluation will be made of alternate boost pump drive methods, such as hydraulic turbine, hot gas

turbine, gear drive, and multi-roller drive, the most promising approach selected for a particular engine size for both fuel and oxidizer boost pumps, and experimental units tested.

(5) Vehicle Mass Fraction Improvement – For advanced STS vehicles, reduction of dry weight is very important. In the propulsion system, various components, such as tanks, propellant lines, valves, manifolds, and thrust chambers can be made lighter in weight by application of composite or filament wound structures. Advanced lightweight moldable composite materials and use of graphite, boron, or Kevlar filament winding will be investigated.

(6) Low/Intermediate Chamber Pressure Technology (Priority 2) – In this category, technology work is needed on low pressure combustion performance and stability for large pressure-fed engines. Also, investigation is needed of performance of existing engines, such as Atlas and Thor engines, with higher density hydrocarbon fuels which could replace RP-1 and provide payload improvements.

(B) High Performance Hydrogen Fueled Systems – The detailed propulsion technology program for the Class II High Performance Hydrogen Fueled Systems is shown in figure 24. The program includes the priority 1 technology for under 30K thrust bell and plug nozzle engines and priority 2 technology for over 250K thrust bell and plug nozzle engines. The technology also is applicable to the Class III under 30K thrust dual fuel engines in the near term time period.

(1) Advanced Space Engine (ASE) Technology – In this area technology work has been in progress under Lewis Research Center sponsorship since 1972 to develop technology for a high pressure, staged combustion cycle hydrogen-oxygen engine[5] suitable for Space Tug. Engine component technology work has included investigation of regenerative thrust chamber performance and cooling, injector development, preburner performance, igniters, main fuel and oxidizer turbopumps, boost pump drive, chamber life at reduced pressure, and bearings and seals life. In the future, the program will be extended to provide evaluation of turbopump life with long-life bearings and seals installed and demonstration of thrust chamber life at full operating pressure. Much of this activity is designed to have general applicability to advanced hydrogen-oxygen engines regardless of the nozzle (bell or plug) or turbopump drive cycle (expander, gas generator, or staged combustion). It therefore provides propulsion system technology suitable for a variety of advanced vehicles.

(2) Powerhead Breadboard Assembly (PBA) – Systems level testing of the powerhead of the staged combustion engine is essential to lay the groundwork for development of an engine of this type. The PBA includes the main regenerative thrust chamber, main injector, preburner, main fuel and oxidizer turbopumps, and controls. Tests of this engine system assembly are essential to evaluate component interaction effects, determine control requirements, and demonstrate successful system operation for transient and steady-state conditions. An optional second phase of this activity is to add the engine boost pumps and their drive system to the PBA to complete the engine system. This system would also be tested at tank head idle and pumped idle conditions.

(3) Plug Nozzle Engine Technology – Technology is needed for plug nozzle engines in the areas of aerospike thrust chamber performance and structural integrity, aerospike segment life, plug cluster nozzle performance, and breadboard engine demonstration. Tests of a full 25,000 pound thrust aerospike chamber will be completed to obtain altitude specific impulse data and verify the structural aspects of a lightweight design. Cyclic tests are needed to determine the thermal fatigue cyclic life of the two-dimensional throat copper alloy segments of the aerospike chamber.[6] The plug cluster nozzle arrangement (figure 14) offers attractive advantages of short engine length and high performance through altitude compensation (for booster engines) and full utilization of vehicle base area for exhaust gas expansion. Evaluation is needed of plug cluster nozzles for specific applications involving clustering around circular or linear plug nozzles to determine performance losses associated with exhaust gas flow from many discrete throats onto the plug. Installed engine weight calculations are needed to allow comparison with alternate approaches. Breadboard engine tests are needed of the aerospike thrust chamber with the main fuel and oxidizer pumps to evaluate expander cycle operation, investigate manifolding problems, and determine control requirements.

(4) Propellant Characterization. (Priority 2) – Studies are needed of the use of slush or triple point hydrogen and oxygen propellants in advanced vehicles. This method can provide increases in propellant density up to 15%, which allows reduction in vehicle size and dry weight. Experimental work is required to evaluate production methods, handling, storage, transfer, pumping, and engine operation.

(5) Thrust Chamber/Combustor Technology. (Priority 2) – Continued advances in large hydrogen-oxygen bell nozzle engine performance are achievable through increases in chamber pressure and use of deployable nozzles. Experimental testing is needed of extendible nozzles capable of being deployed during engine operation and thus provide a nozzle expansion ratio more closely matched to the optimum area ratio for the prevailing nozzle pressure ratio, which varies from sea level takeoff conditions to space vacuum. Testing is also required to evaluate performance and thrust chamber cooling at higher chamber pressures up to 4000 psia.

(C) Solid Rocket Motors – The detailed propulsion technology program for Class VI, Solid Rockets, is shown in figure 25. This program encompasses work for both large and small thrust motors for the near term requirements.

(1) Propellant Technology – Improvements in solid propellant technology are needed in the areas of propellant cost, atmospheric pollution, and performance. Propellant formulation studies are needed to develop a new propellant with enhanced energy content, mechanical properties, case bondability, and combustion characteristics while maintaining acceptable hazard classification for use in vehicles such as Space Shuttle and Tug.

(2) Improved Components – Various improvements to solid rocket components are needed such as reduction of the cost and weight, of the case and nozzle. Design, fabrication, and hydrotesting of segments of a 140-inch diameter filament wound fiberglass case are needed to verify application of this technology to SRB size cases. Subscale motor tests are needed to evaluate low cost nozzle materials and low cost chamber insulation materials suitable for the SRB nozzle and motor case. To reduce case and nozzle weight, high strength carbon materials should be evaluated including investigation of manufacturing methods using carbon filaments.

(3) Solid Motor System – Technology demonstration is needed of an optimized high energy kick stage motor with TVC and multiple burn capabilities using Class 2 propellants. This effort should include analysis and trade-off studies leading to design, fabrication, and testing of subscale and full scale motors. This work is needed to provide a Class 2, high performance, low cost solid propulsion option for Shuttle missions.

(D) Recommended Priority 2 Studies

(1) SRB Replacement Study – This study would evaluate various proposed vehicle concepts (see figure 11) that eliminate the Shuttle SRB's in order to significantly reduce recurring cost per launch. These include use of liquid strap-on boosters recoverable by parachute or flown back as RPV's manned heat sink flyback boosters, or other options that utilize all or part of the present Shuttle hardware. The study would provide comparative data on vehicle GLOW and dry weight, propulsion system characteristics, propellant types and quantities required, oprational constraints, recurring and non-recurring cost projections, and details of technology advancements required.

(2) SSME Improvement Study – A study program to evaluate uprating and/or improvements to the Space Shuttle Main Engine, including, for example, investigation of higher chamber pressure operation, engine dry weight reduction, and use of an extendible nozzle. The study would provide data on engine performance and weight, and cycle balance data, such as temperatures, pressures, flows, and turbopump speeds at key points throughout the engine system. Preliminary designs would be completed on components of the engine requiring modification and details provided of life predictions for critical components.

(3) Shuttle OME Improvement Study – This program would investigate changes to the Space Shuttle Orbit Maneuvering Propulsion System to reduce weight, reduce propellant cost, reduce operational and handling problems and constraints, improve performance, and reduce turnaround time between flights. The study would evaluate alternate propellants, e.g., LOX-hydrocarbon or LOX-amine fuel, and higher performance pump-fed engines using these propellants or the N_2O_4-MMH propellants now baselined for the OME. Selection would be made of the most favorable approaches for making improvements and technology work planned to lay the groundwork for these changes.

(4) Space Tug Applications Study – This study would evaluate the requirements for the Space Tug after the IUS decision has been made, taking into account any revisions in Tug missions due to changes in Shuttle capability, mission model revisions, or Tug development schedule revisions. The study would also consider alternative design approaches, such as use of cryogenic propellants, earth storables, or high performance high density propellants, (LOX-hydrocarbon or LOX-amine fuel) or a mixed mode system with dual fuel engine. In the case of cryogenic propellants, alternate engines would be considered at constant conditions of engine thrust, operating capabilities, and mixture ratio. The effect of tug length would be fully evaluated and determination made of the value of short length and high performance in reducing Shuttle flights and attendant launch cost per pound of payload through multiple-payload packaging.

SUMMARY

A plan has been presented for generation of primary propulsion technology to meet the projected needs of advanced space transportation systems in the years from 1980 to 2000, which was divided into the near term (1980's) and far term (1990's) periods. The propulsion systems for these applications were divided into two major thrust levels: (1) 5,000 to 30,000 pounds thrust and (2) over 250,000 pounds. The study considered only chemical rocket propulsion, not nuclear or electric, and subdivided the applicable propulsion systems into six classes, including liquid bi-propellants, solids, and composite (rocket/air breathing) engines.

The propulsion technology plan is based upon the following assumptions:

(1) Chemical rocket propulsion will continue to be the propulsion workhorse of the space program throughout the 1980-2000 time period and will be utilized for most of NASA's primary propulsion needs.

(2) No major breakthroughs in chemical propulsion technology are evident that are likely to be applied during this time period. The technology efforts described are therefore evolutionary in nature. The state-of-the-art in chemical propulsion systems can be greatly improved by an accumulation of small improvements. Realization of this fact provides justification for a broadly based propulsion technology program, since not all gains sought will prove to be attainable and since each incremental gain, by itself, may be difficult to justify. However, the additive effects of, for example, operation at higher pressure, use of mixed mode propulsion, increased propellant density, and use of dual fuel engines, can provide very significant payload gains or vehicle size and weight reductions.

(3) Long lead times are needed to develop new propulsion technology, typically 5-10 years. An additional 5-10 years is needed for vehicle development. It is, therefore, essential to initiate work on advanced concepts at once in order to provide improved capability as early as 1985.

(4) Systems level testing is generally needed to provide an adequate technology base so that advanced propulsion concepts will be selected for use on a flight vehicle.

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TABLE I

HYDROCARBON FUEL CHARACTERISTICS

Fuel	Formula	Fuel Density gms/cc	Propellant Density lbs/ft3	Specific Impulse (Note 1)	Cost Cents/lb
Methane	CH_4	0.43	50.5	308.0	6
RP-1	$C_{12}H_{24}$	0.80	63.3	296.4	7
TH-Dimer	$C_{10}H_{16}$	0.92	66.4	298.0	21
RJ-5	$C_{14}H_{18}$	1.08	70.19	293.0	>100
H-COT	$C_{16}H_{20}$	1.13	71.29	292.0	>100
1-7 Octadiyne	C_8H_{10}	0.81	62.8	307.5	70
Bicyclo-Butane	C_4H_6	0.75	61.1	313.9	>100
Acetylene	C_2H_2	0.62	55.1	325.0	35

NOTE 1: Stoichiometric Mixture with LOX; Equilibrium Expansion from 1000/14.7 psia

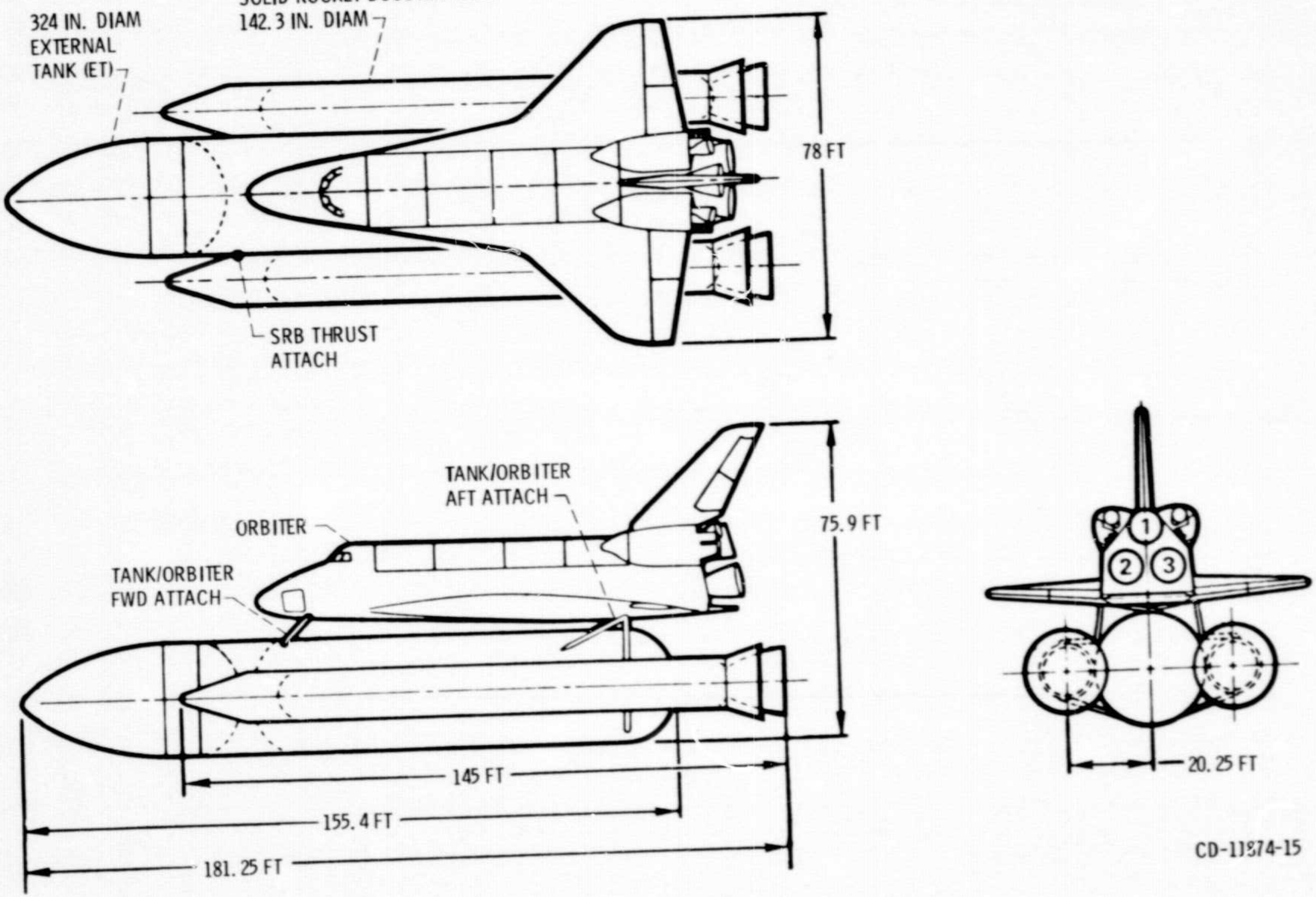


Figure 1. - Space shuttle vehicle.

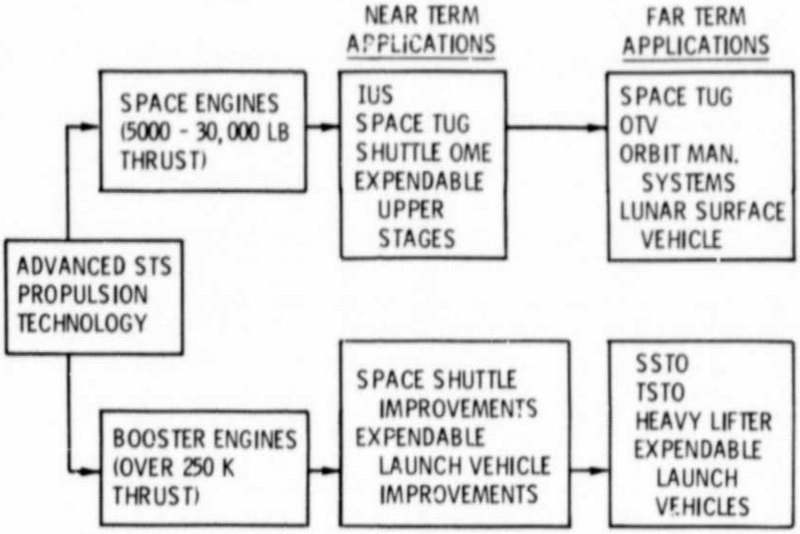


Figure 2. - Technology flow-advanced space transportation systems - primary propulsion.

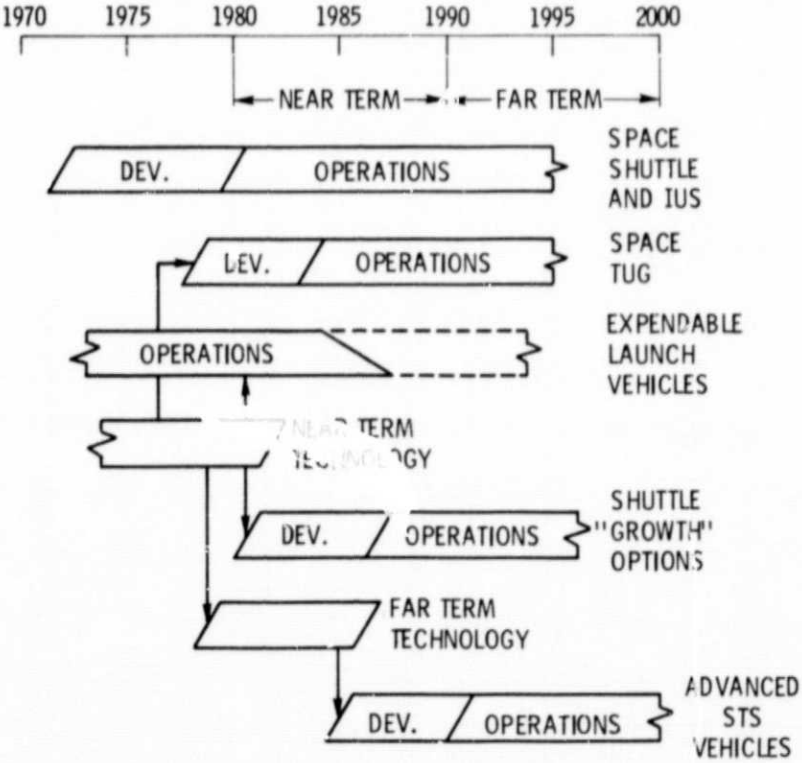


Figure 3. - Advanced space transportation systems propulsion technology planning.

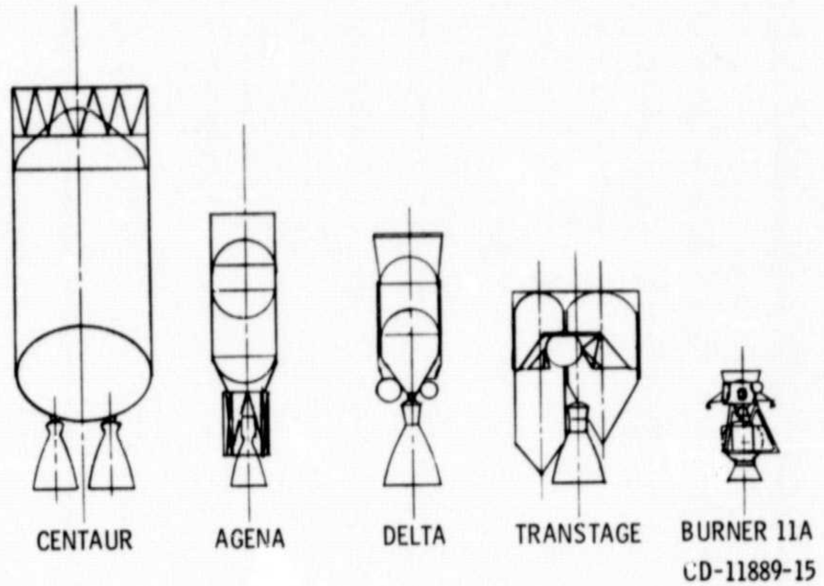


Figure 4. - Baseline expendable shuttle upper stage configurations.

E-8443

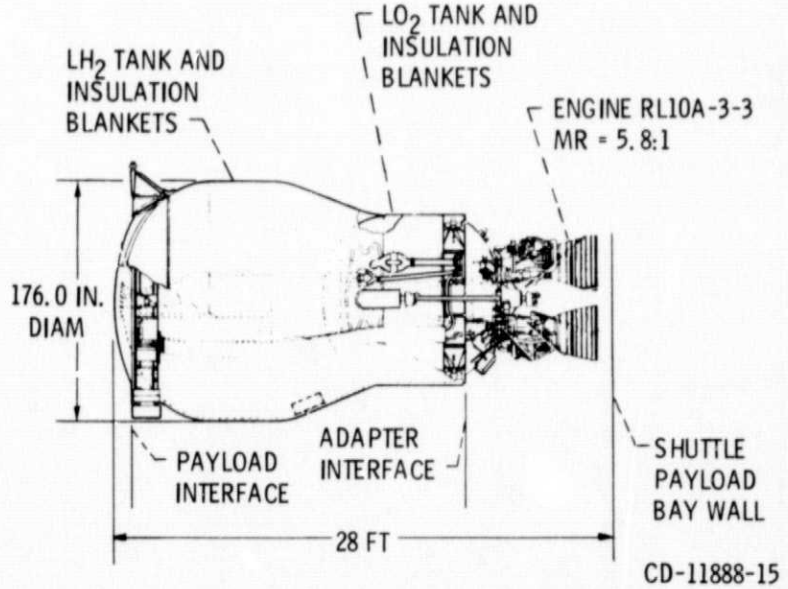


Figure 5. - Modified Centaur interim upper stage.

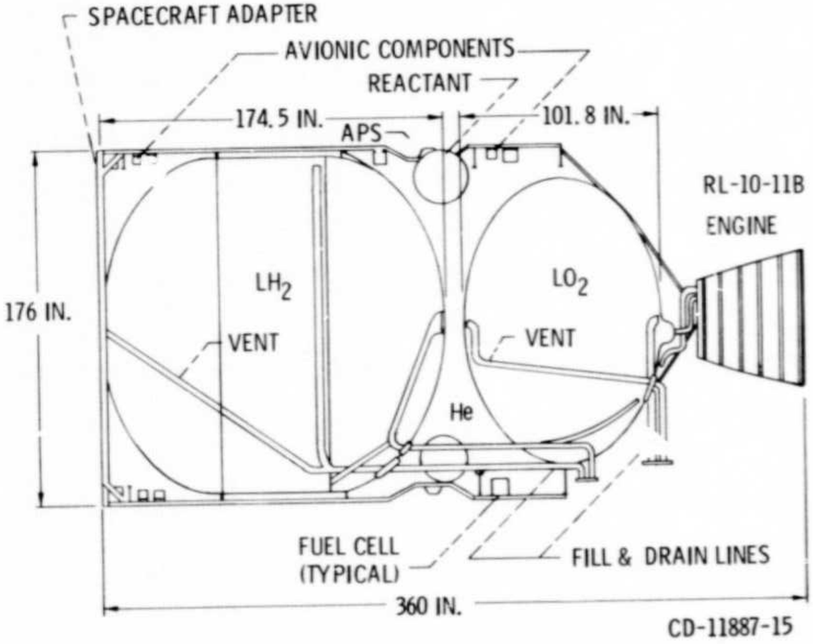
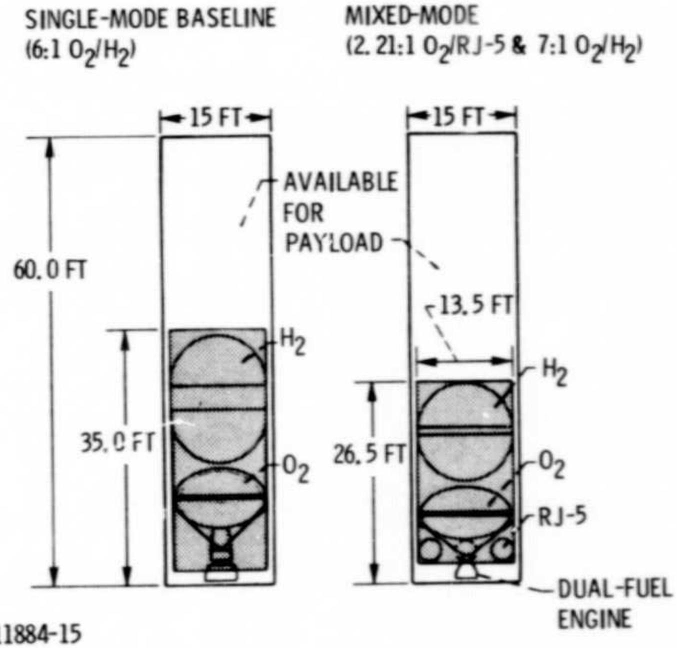


Figure 6. - Baseline cryogenic space tug.



GROSS WT. LESS P/L, LB	62 000	62 162
PROP. VOL., FT^3	2 470	1 850
DRY WT., LB	5 223	4 920
PAYLOAD, LB (GEOSYNCH)		
ROUND TRIP	3 300	3 000
ONE-WAY UP	8 350 (18 450 EXP.)	8 600 (18 000 EXP.)
ONE-WAY DOWN	5 100	5 270

Figure 7. - Comparison of single-mode and mixed-mode tugs in the shuttle payload bay.

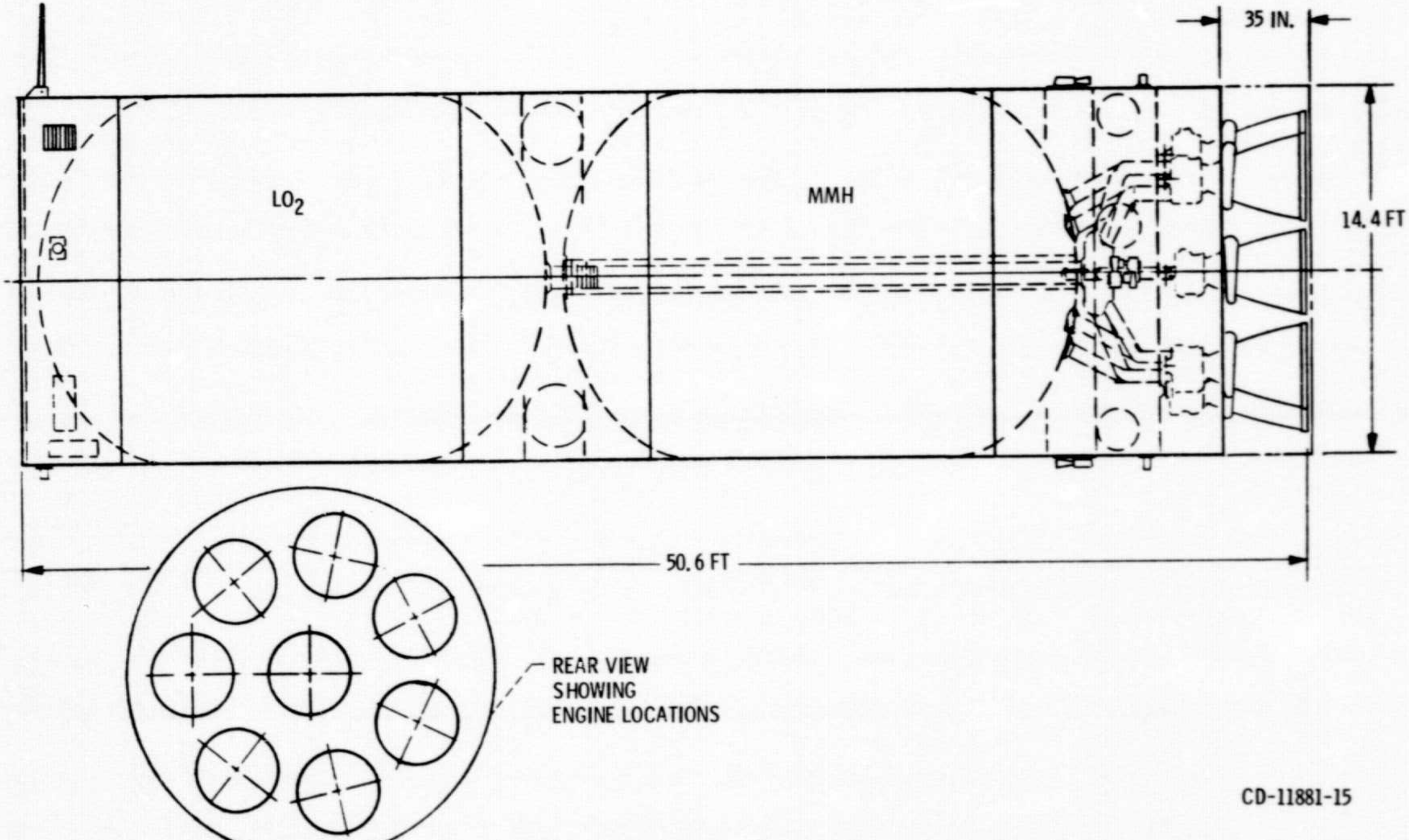


Figure 8. - LO_2/MMH orbit transfer vehicle.

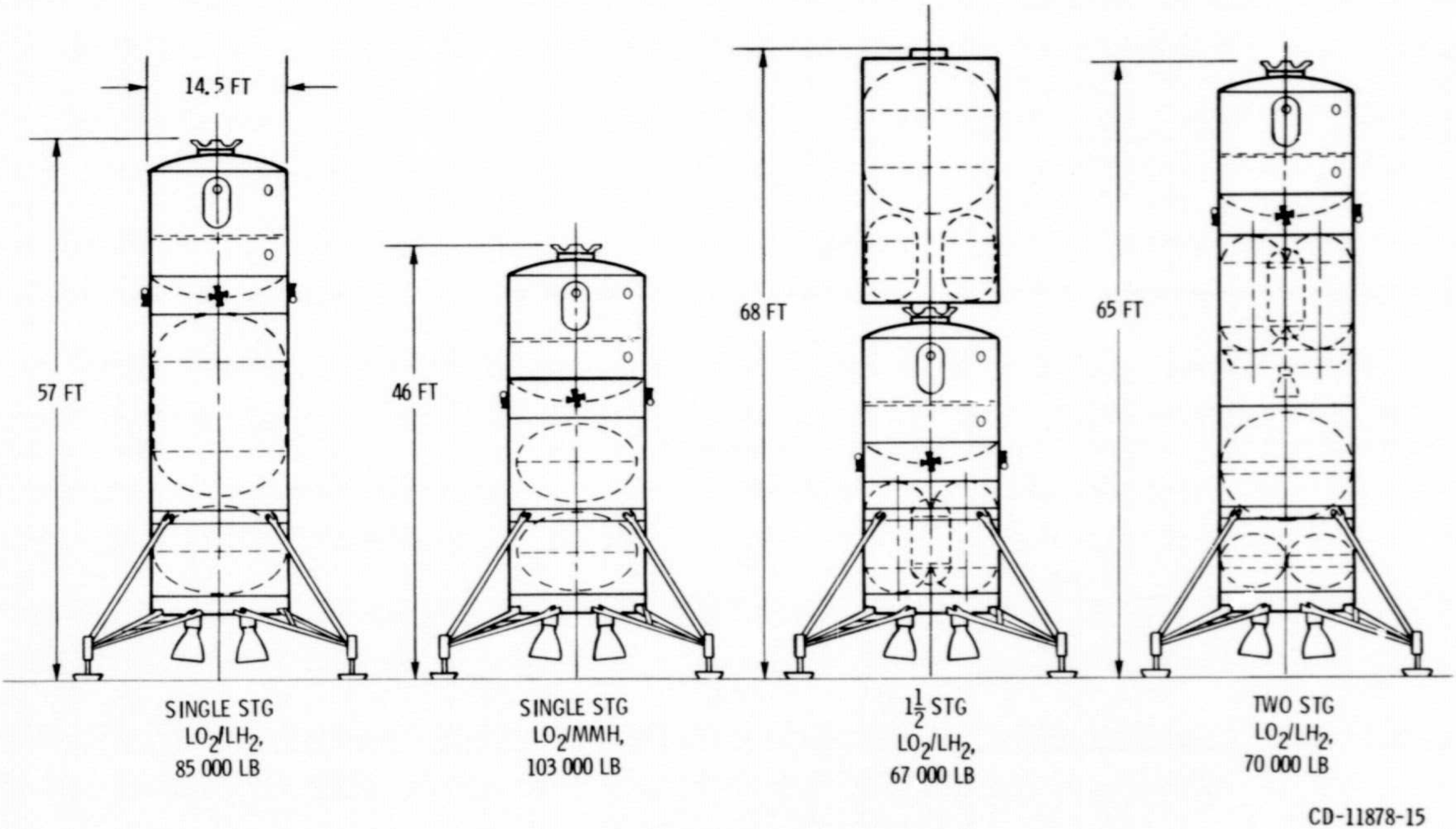


Figure 9. - Representative lunar surface vehicles.

THRUST, LB	
SEA LEVEL	375 000
VACUUM	470 000
CHAMBER PRESSURE, PSIA	2970
NOZZLE AREA RATIO	77.5
SPECIFIC IMPULSE (NOM), SEC	
SEA LEVEL	363.2
VACUUM	455.2
MIXTURE RATIO (O/F)	6.0
LENGTH, IN.	167
NOZZLE EXIT DIAMETER, IN.	94
WEIGHT, LB	6335
LIFE	
HOURS	7.5
STARTS	55

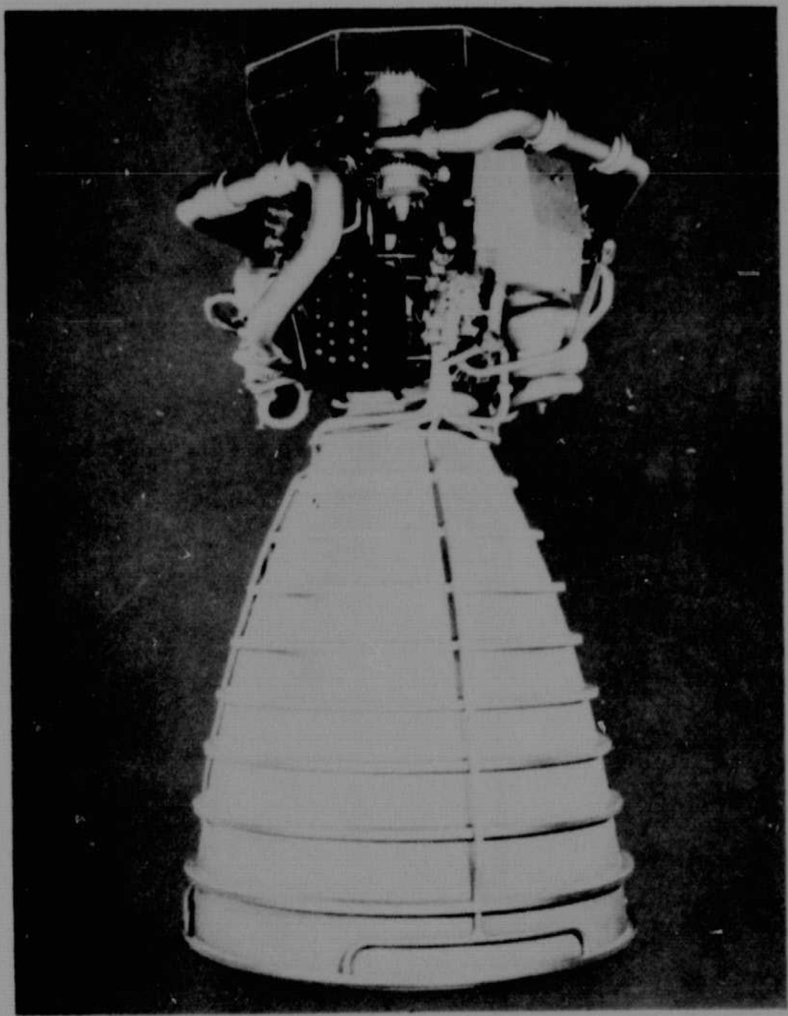


Figure 10. - Space shuttle main engine.

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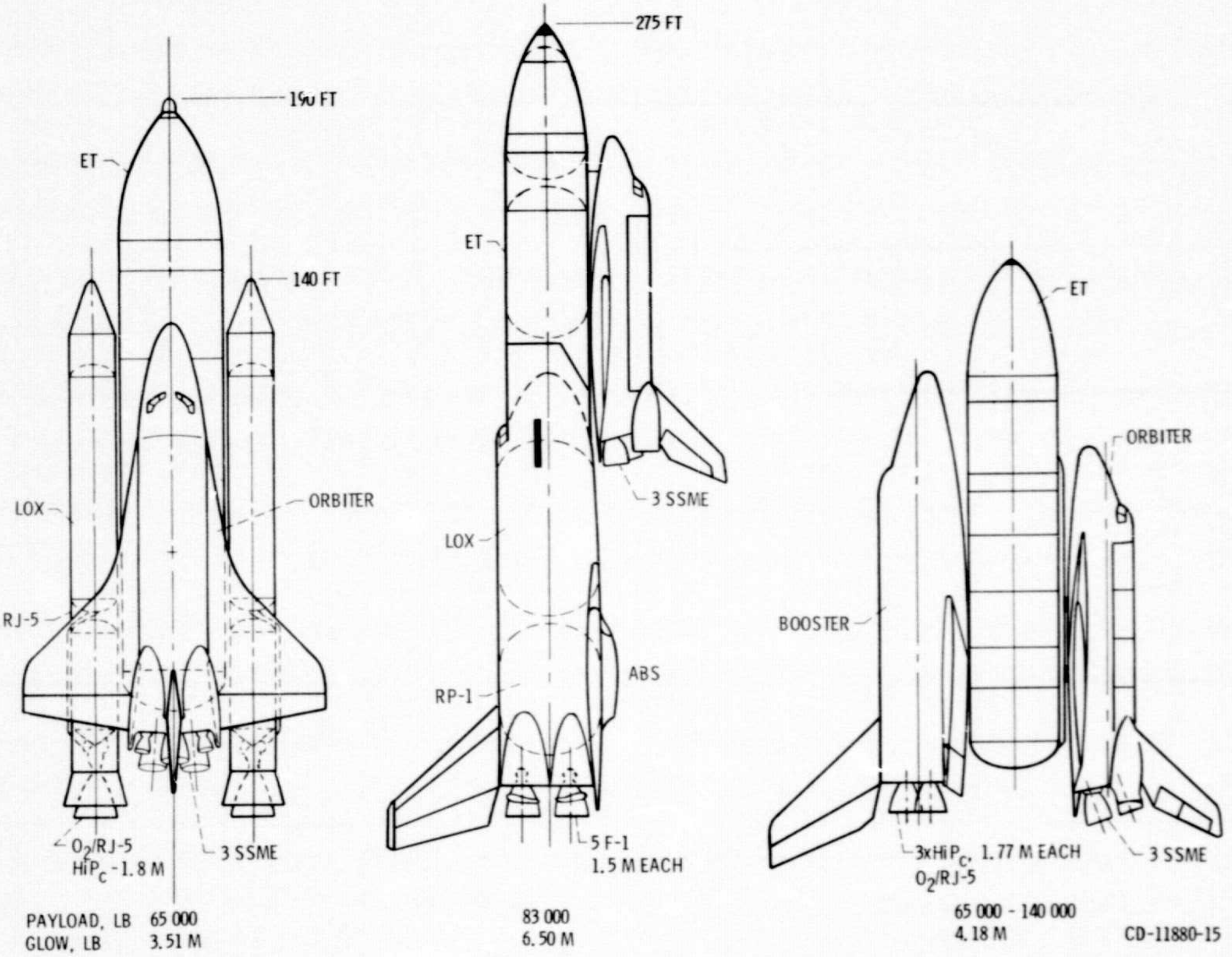
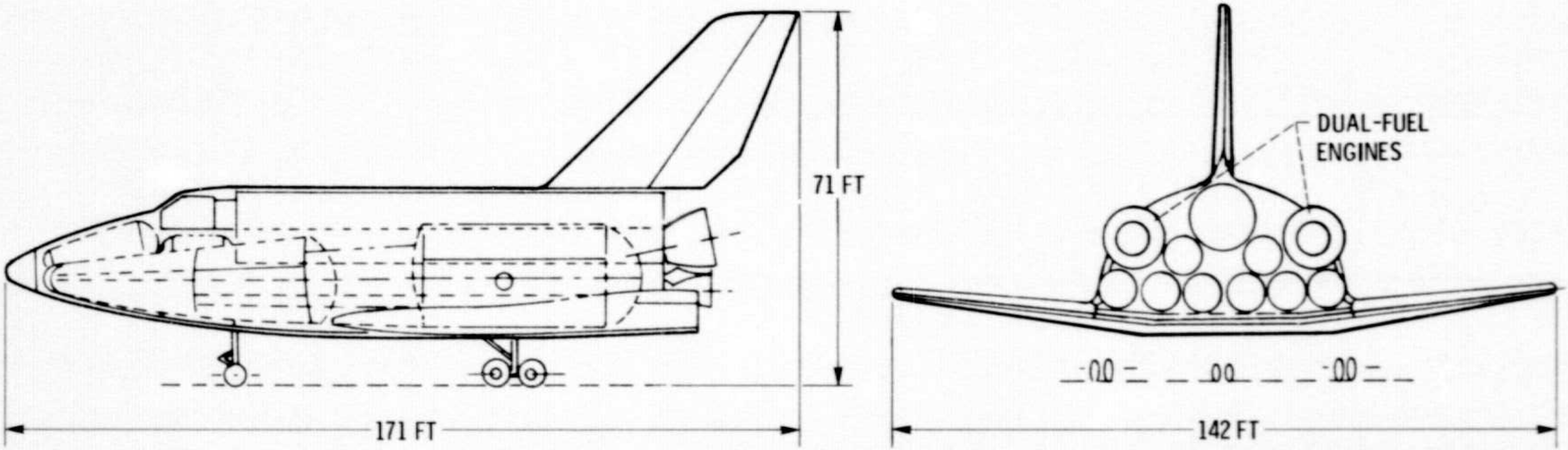


(a) DUAL LOX/RJ-5 BOOSTERS.

(b) FLYBACK HEAT SINK BOOSTER.

(c) FLYBACK BOOSTER (PHASE I OF TWO-STAGE, FULLY REUSABLE SYSTEM).

Figure 11. - Examples of shuttle growth options (no SRB's).



MAIN PROPULSION

8 x 680 K S.L. (O_2/RJ-5; ε = 60)

2 x 680 K S.L. (O_2/RJ-5/H_2; ε = 60 & 200)

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Figure 12. - Mixed-mode single-stage shuttle configuration.

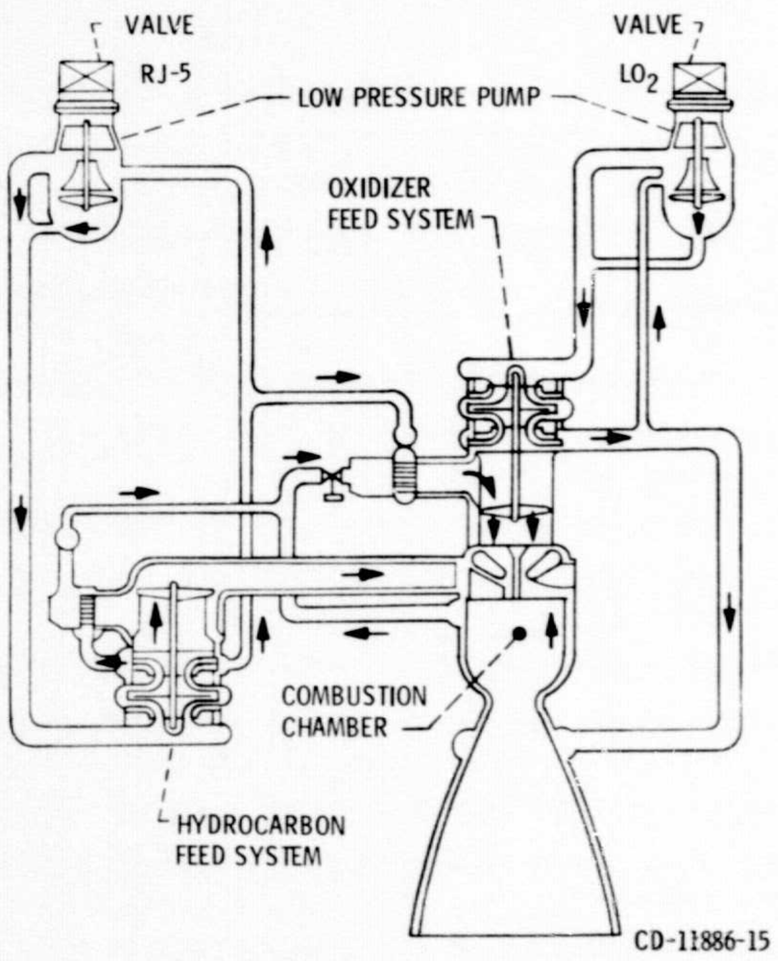

Figure 13. - High pressure LO_2/RJ-5 engine schematic.

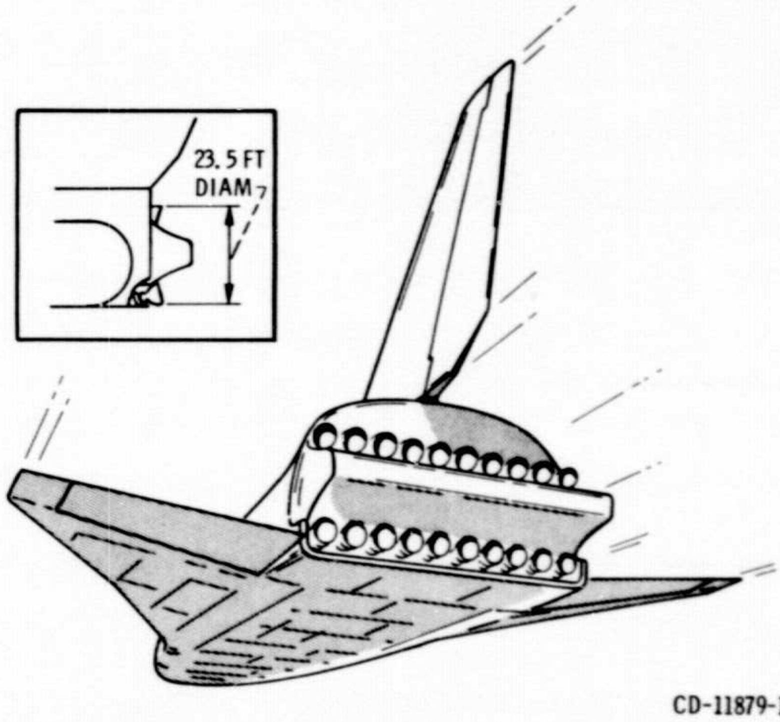

Figure 14. - SSTO vehicle with linear plug nozzle - gimbaled engines.

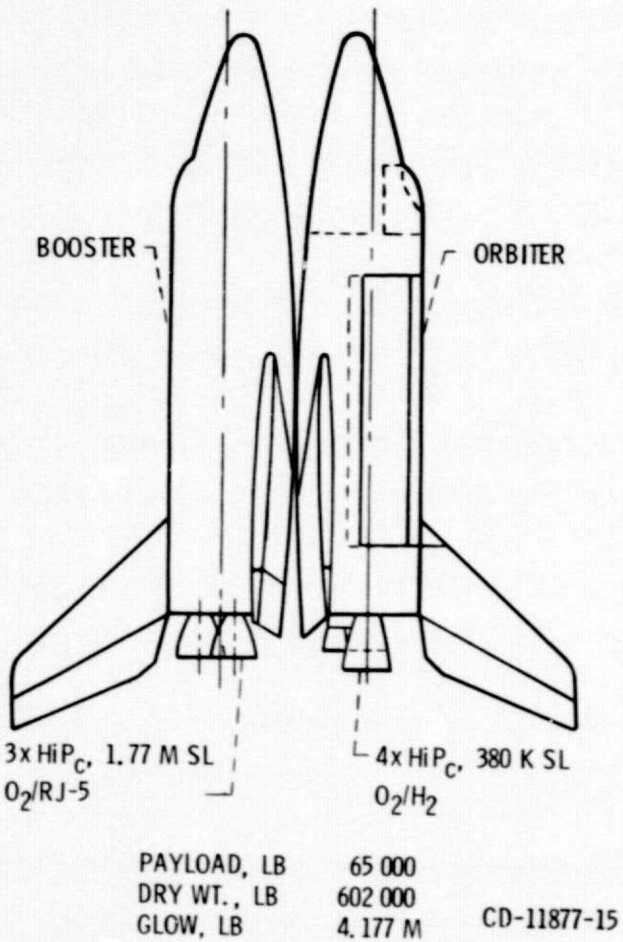

Figure 15. - Two-stage-to-orbit fully reusable shuttle vehicle.

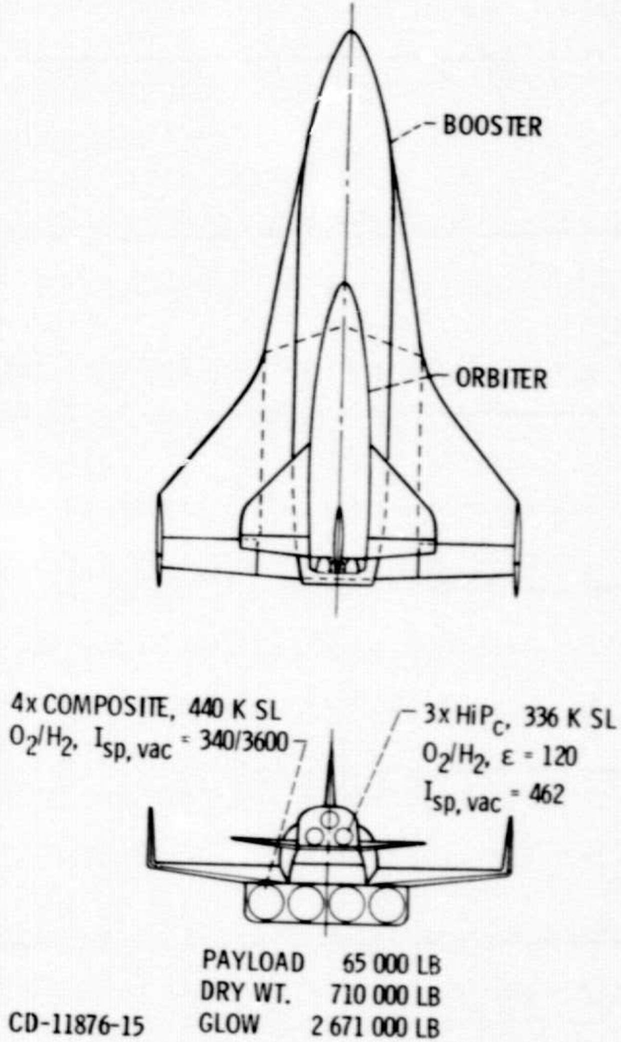

Figure 16. - HTOHL two-stage-to-orbit vehicle using composite engines.

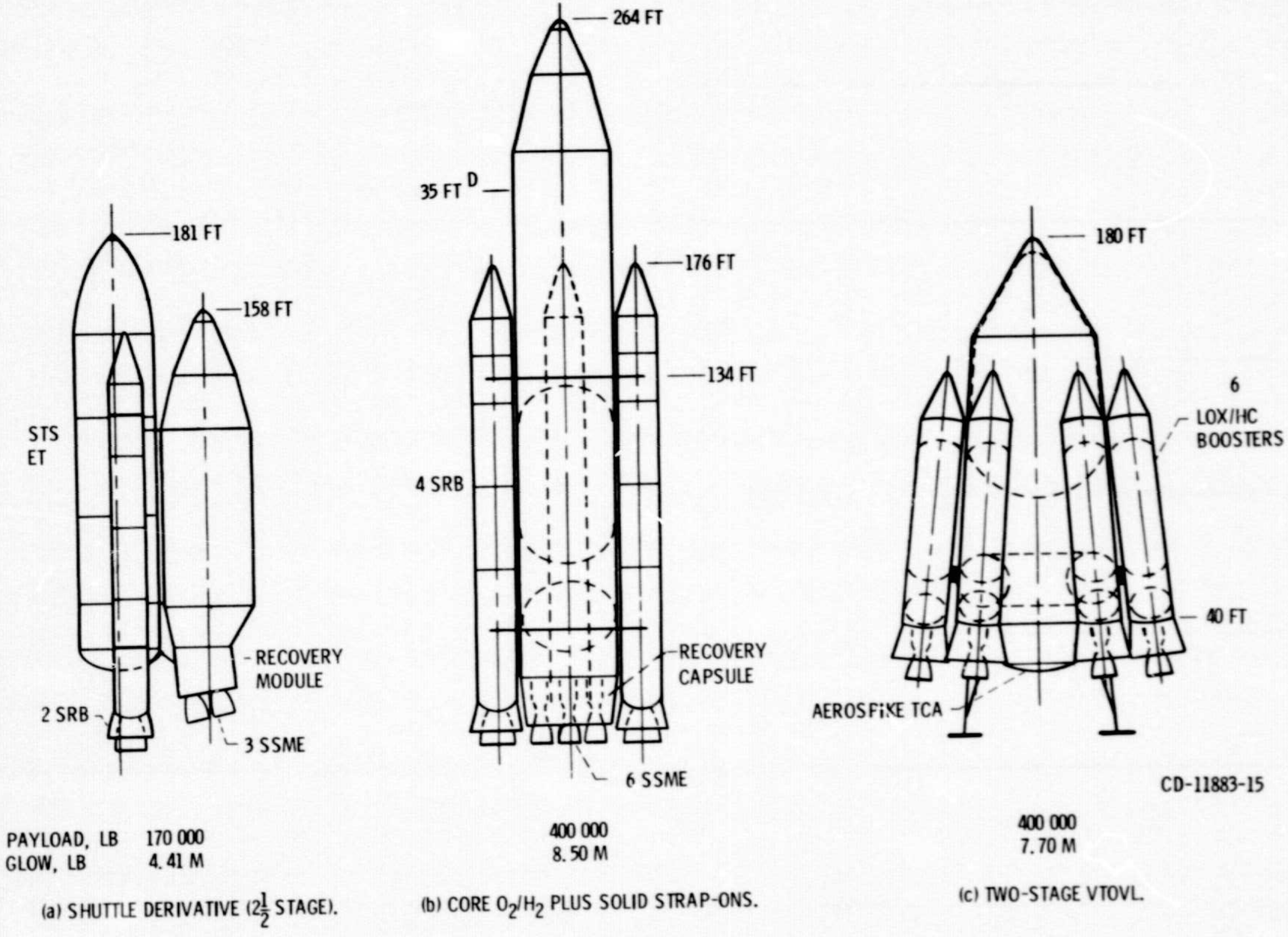

Figure 17. - Examples of heavy lift vehicles.

CLASS NO.	CLASS NAME	SUBDIVISIONS	NEAR TERM APPLICATIONS									FAR TERM APPLICATIONS								
			<30 K THRUST				>250 K THRUST					<30 K THRUST				>250 K THRUST				
			INTERIM UPPER STAGE (IUS)	SPACE TUG	SHUTTLE OME	EXPENDABLE UPPER STAGES	SSME IMPROVEMENT	SRB IMPROVEMENT	SRB REPLACEMENT	EXP. LAUNCH VEHICLE IMPR.		SPACE TUG	ORBIT TRANSFER VEHICLE	ORBIT MANEUVERING SYSTEM	LUNAR SURFACE VEHICLE	SINGLE STAGE-TO-ORBIT (SSTO)	TWO STAGE- TO-ORBIT	SSTO/ ASSISTED TAKEOFF	EXPENDABLE VEHICLE LAUNCH	HEAVY LIFT VEHICLE
I.	HIGH PERFORMANCE, HIGH DENSITY FUELED SYSTEMS	BELL NOZZLE ENGINES		✓	✓				✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
		PLUG NOZZLE ENGINES		✓					✓			✓	✓		✓	✓	✓	✓		✓
		FLUORINATED OXIDIZERS	✓			✓						✓								
II.	HIGH PERFORMANCE, HYDROGEN FUELED SYSTEMS	BELL NOZZLE ENGINES	✓	✓	✓	✓	✓					✓	✓	✓	✓	✓	✓	✓		✓
		PLUG NOZZLE ENGINES	✓	✓					✓			✓	✓		✓	✓	✓	✓		✓
		FLUORINATED OXIDIZERS	✓			✓						✓			✓					
III.	HIGH PERFORMANCE, DUAL-FUELED SYSTEMS	BELL NOZZLE ENGINES		✓								✓	✓			✓		✓		
		PLUG NOZZLE ENGINES		✓								✓	✓			✓		✓		
IV.	LOW DEVELOPMENT COST, HIGH DENSITY FUELED SYSTEMS	LOW PRESSURE (<1000 PSIA) PUMP-FED ENGINES	✓	✓	✓				✓	✓			✓	✓	✓	✓	✓	✓	✓	✓
		PRESSURE-FED ENGINES			✓				✓				✓	✓	✓		✓			✓
V.	COMPOSITE (ROCKET/AIR BREATHING) SYSTEMS	AIR AUGMENTATION						✓		✓							✓	✓	✓	
		RAMJETS, TURBOROCKETS, LACE, ETC.															✓	✓		
VI.	SOLIDS	BELL NOZZLE ENGINES	✓			✓		✓		✓								✓		✓

Figure 18. - Propulsion system classifications and applications.

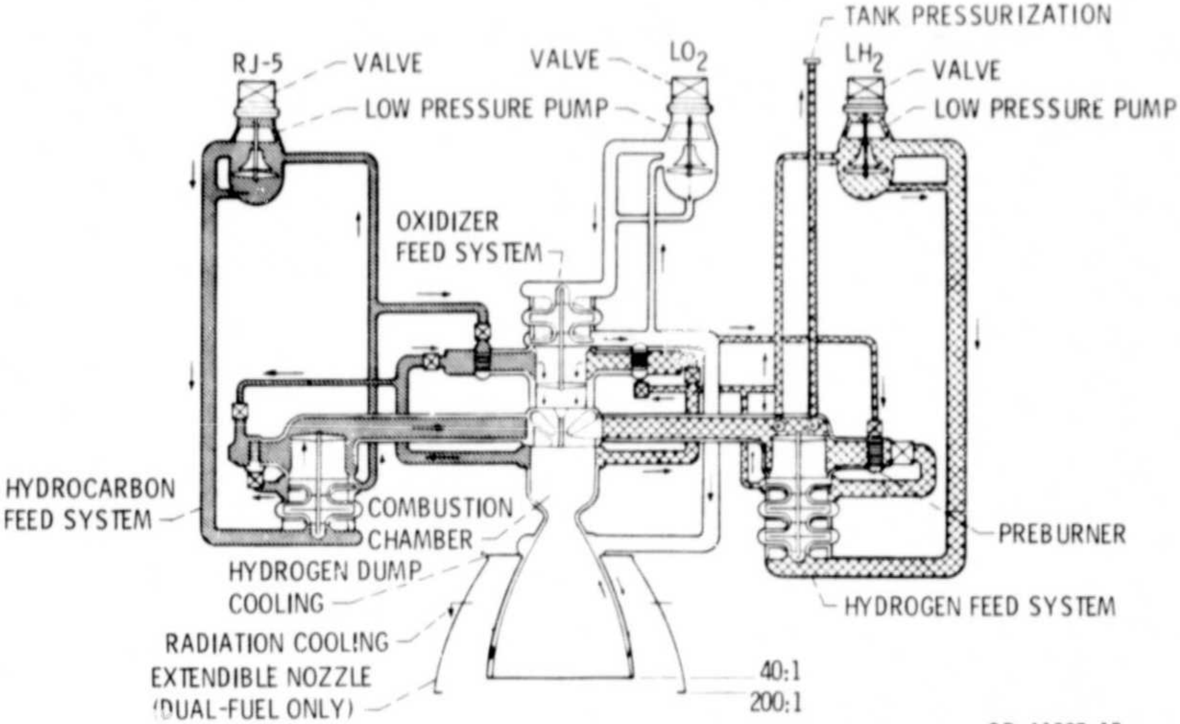

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Figure 19. - Dual-fuel engine schematic.

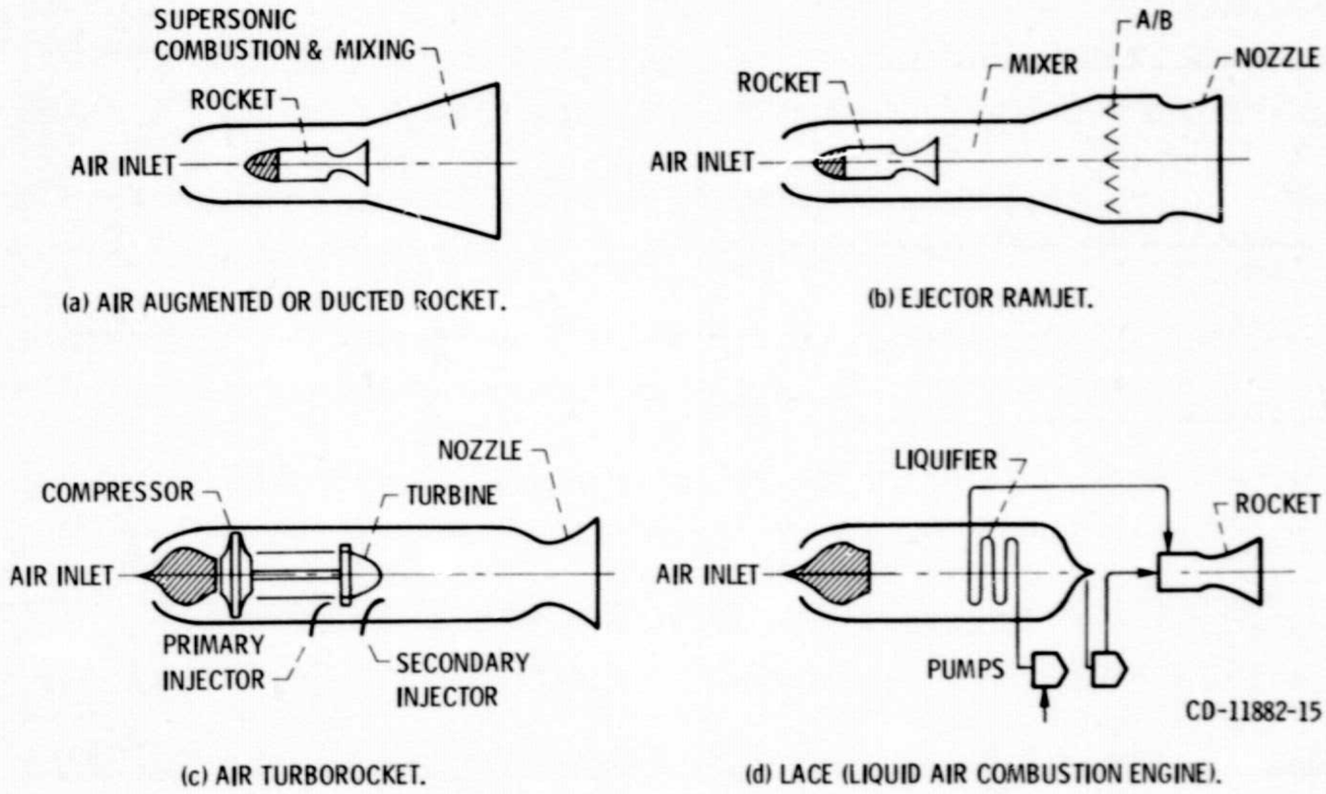

Figure 20. - Basic types of composite engines.

CLASS NO.	CLASS NAME	SUBDIVISIONS	NEAR TERM		FAR TERM	
			<30K	>250K	<30K	>250K
I.	HIGH PERFORMANCE, HIGH DENSITY FUELED SYSTEMS	BELL NOZZLE ENGINES	2	1	2	1
		PLUG NOZZLE ENGINES	3	2	3	2
		FLUORINATED OXIDIZERS	3	N/A	2	N/A
II.	HIGH PERFORMANCE, HYDROGEN FUELED SYSTEMS	BELL NOZZLE ENGINES	1	2	1	2
		PLUG NOZZLE ENGINES	1	2	1	2
		FLUORINATED OXIDIZERS	3	N/A	2	N/A
III.	HIGH PERFORMANCE, DUAL-FUELED SYSTEMS	BELL NOZZLE ENGINES	3	N/A	3	2
		PLUG NOZZLE ENGINES	3	N/A	3	2
IV.	LOW DEVELOPMENT COST, HIGH DENSITY FUELED SYSTEMS	LOW PRESSURE (<1000 PSIA) PUMP-FED ENGINES	2	2	2	2
		PRESSURE-FED ENGINES	2	3	3	3
V.	COMPOSITE (ROCKET/AIR BREATHING) SYSTEMS	AIR AUGMENTATION	N/A	3	N/A	2
		RAMJETS, TURBOROCKETS, LACE, etc.	N/A	N/A	N/A	2
VI.	SOLIDS	BELL NOZZLE	1	1	3	3

Figure 21. - Priority ratings for advanced propulsion technology.

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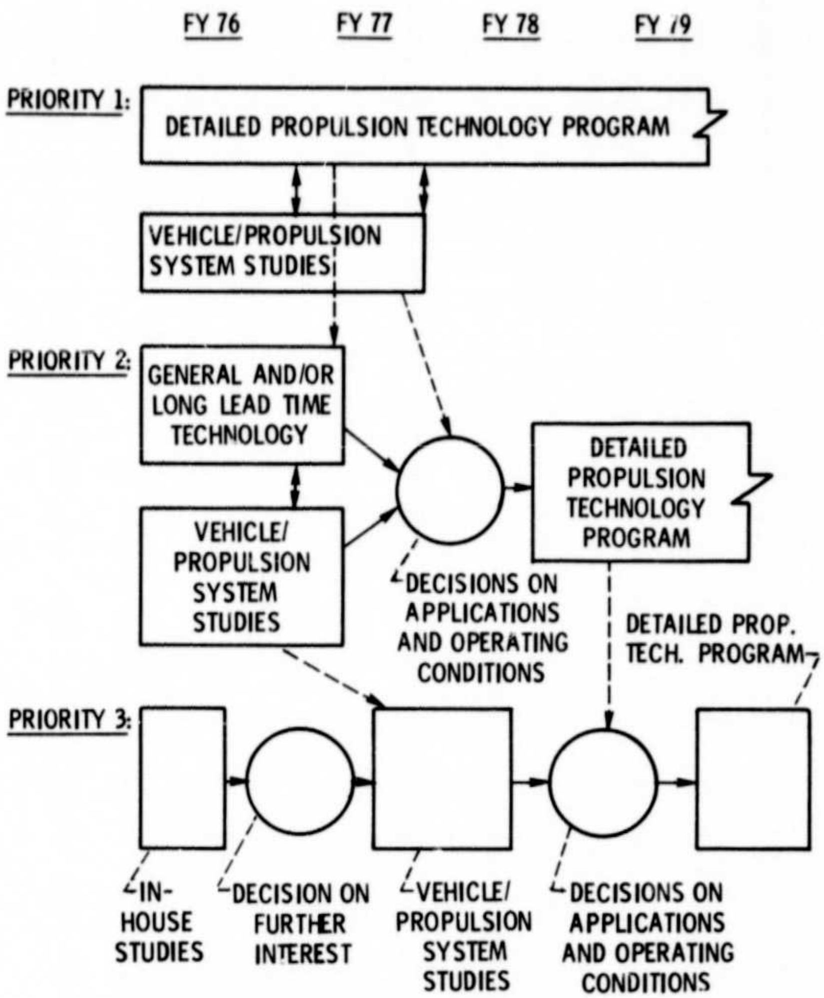

Figure 22. - Near term propulsion technology - program logic.

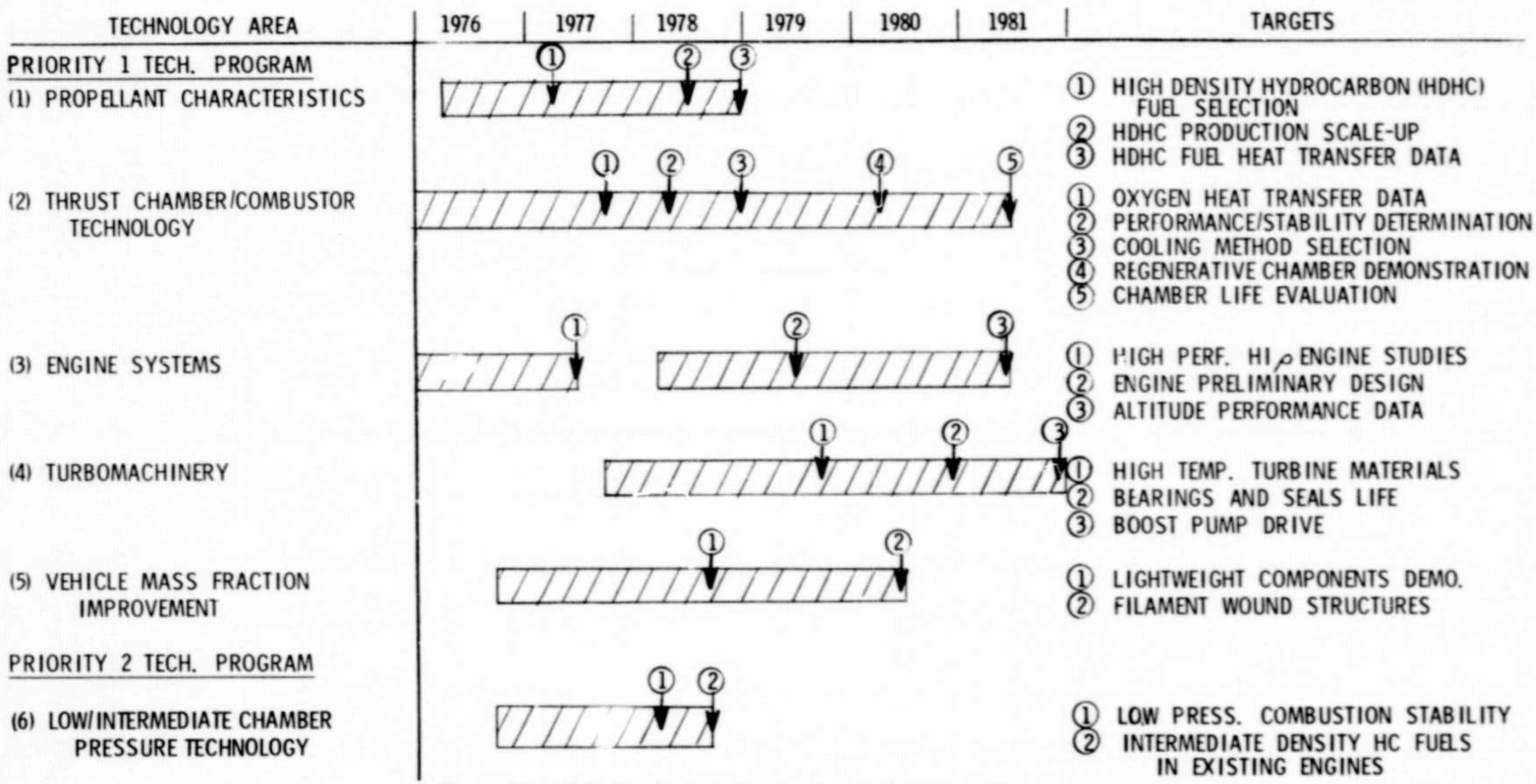

Figure 23. - High density fueled systems near term technology program.

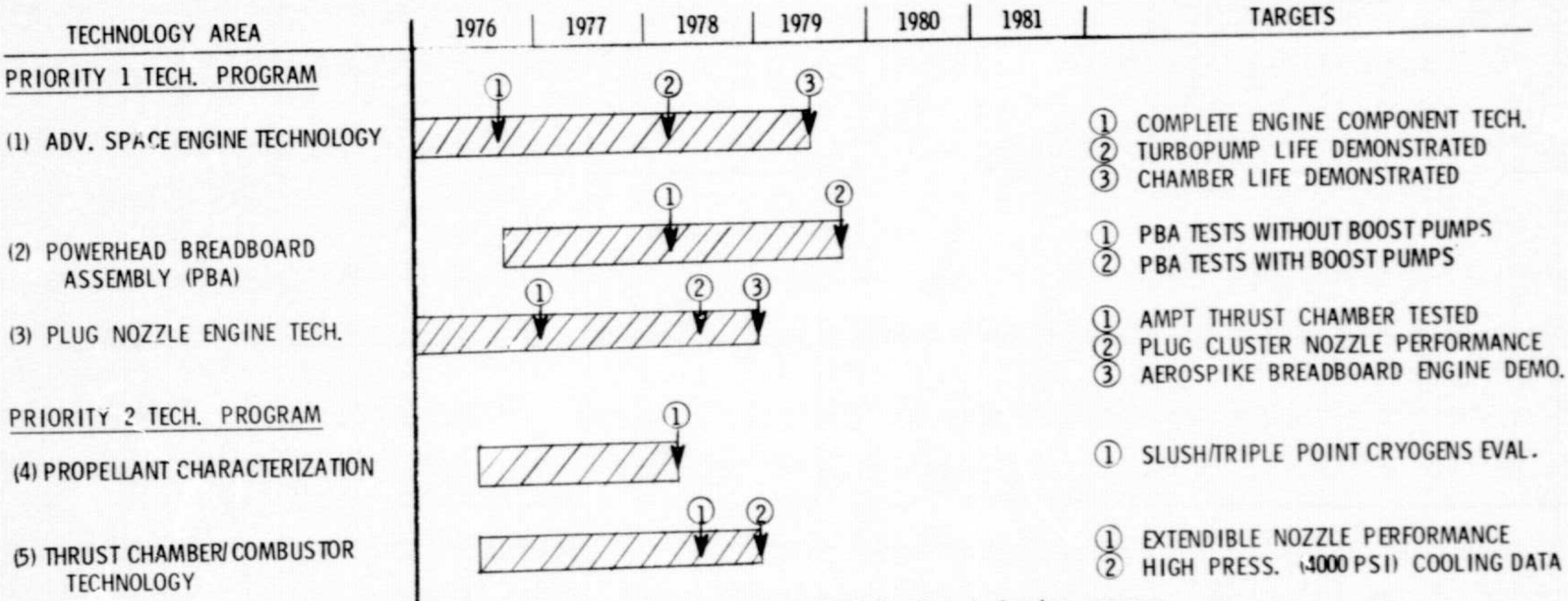

Figure 24. - High performance, hydrogen fueled systems technology program.

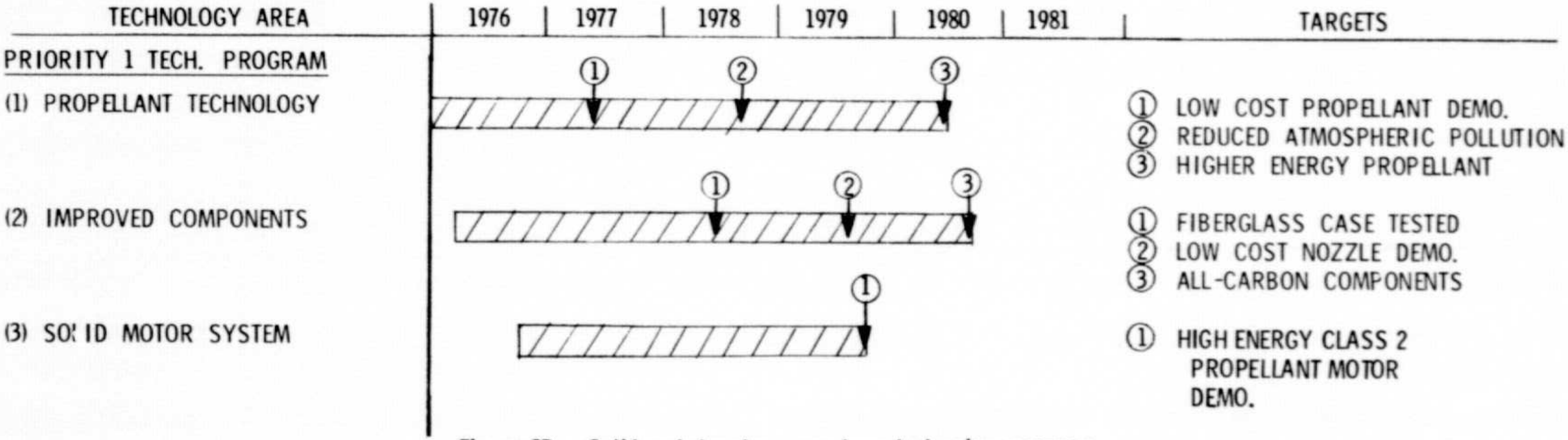

Figure 25. - Solid rocket motors near term technology program.

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